Geomorphology and River Hydraulics of the Teton River Upstream of Teton Dam
Teton River, Idaho

U.S. Department of the Interior
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Section 1

Introduction

The construction and subsequent failure of Teton Dam in 1976 changed the physical and biological characteristics of the Teton River canyon for 17 miles upstream from the dam site. This report documents the existing physical conditions and the changes that have occurred to the geomorphology and river hydraulics in the Teton River canyon as a result of the reservoir inundation and subsequent failure of Teton Dam.

Background

The construction of the Teton Basin Project, Lower Teton Division, was authorized by Public Law 88-583 on September 7, 1964. The Lower Teton Division was to be constructed in two phases in Fremont and Madison Counties, Idaho (figure 1). The first phase included Teton Dam and Reservoir, a powerplant, groundwater wells to provide water in dry years, and other features. This phase would have provided supplemental irrigation water for approximately 110,000 acres in the Fremont-Madison Irrigation District, for flood control operation, and for recreation and fish and wildlife mitigation measures (Schuster and Embree, 1980). The 17-mile-long reservoir was to have a total capacity of 288,000 acre-feet and a surface area of 2,100 acres.

Approximately half the land required for construction of Teton Dam and Reservoir was obtained from private landowners or the State of Idaho. The rest of the land was obtained from the Bureau of Land Management under a Reclamation withdrawal.

Filling of the reservoir began October 3, 1975, and continued until June 5, 1976, when Teton Dam failed (Jansen, 1980). The reservoir was at elevation 5301.7, about 272 feet deep at the dam, and 22.6 feet below the planned maximum pool elevation when piping caused the embankment to fail. Approximately 250,000 acre-feet of water and 4 million cubic yards of embankment material were sent down the river in about 6 hours (Lloyd and Watt, 1981; photograph A-1, in appendix A). The destruction downstream from the dam was extensive, reaching to the upper end of American Falls Reservoir, 95 miles downstream.

The failure of the dam created a situation unparalleled in Reclamation history. Legal experts analyzing the situation determined that the Federal Government was not liable for the flood damage. However, the Administration's standpoint was that the United States had a moral obligation to the flood victims, and a special appropriation was requested to pay for damages. Congress passed the appropriations bill and a subsequent bill introduced by the Idaho Congressional Delegation. Slightly less than $400 million was paid to claimants and to contractors who repaired the flood-damaged infrastructure.

The release of water from the reservoir caused extensive damage to the fisheries and riparian habitat from the dam downstream to the confluence with the Henry's Fork of the Snake River. The Idaho Fish and Game Department was compensated $1,768,708 for the loss of fish production, based on habitat loss, in this stretch of the river.

In addition to the devastation caused downstream, the portion of the Teton River canyon, which was inundated by the 17-mile-long reservoir, and Canyon Creek, a tributary which was inundated for 3 miles, were also affected. Prior to filling the reservoir, riparian and woody vegetation was cleared in the reservoir area (photograph A-34). Wetland, upland, and aquatic vegetation and habitat conditions upstream from the dam were initially impacted as a result of the clearing and then were impacted again by hundreds of landslides that occurred during the filling and subsequent failure of Teton Dam and Reservoir.

Currently, the riverbanks are generally devoid of riparian and woody vegetation and consist almost entirely of reed canary grass. Both upland and wetland riparian and woody vegetation provide valuable habitat for many wildlife species. Following the failure of Teton Dam, the reservoir basin was reseeded with reed canary grass (*Phalaris arundinacea*) to control surface erosion.

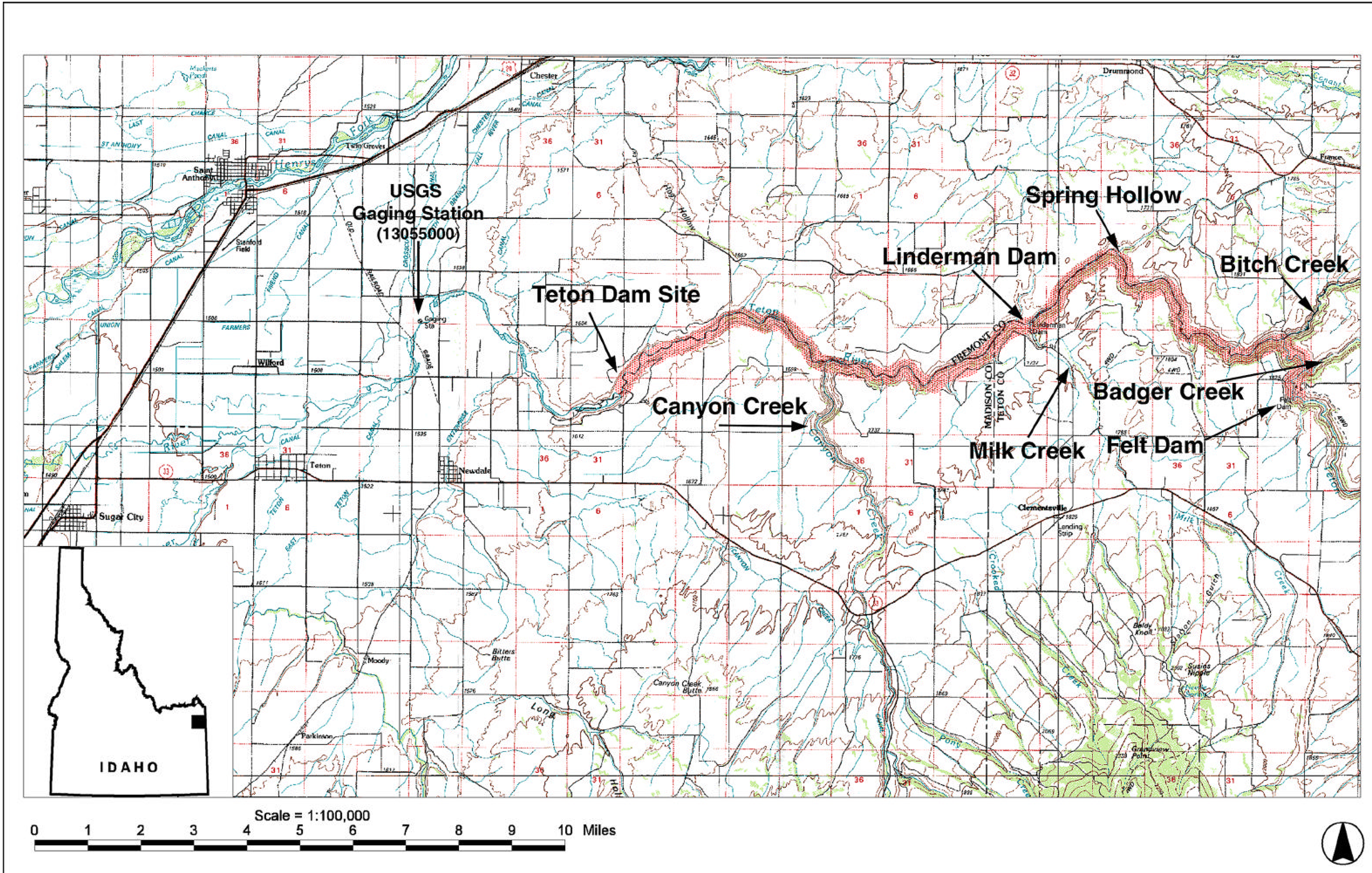
Although the reservoir upstream from Teton Dam would have completely altered the ecosystem, the landslides triggered by the dam failure are also believed to have changed the ecology of the aquatic habitat from predam conditions. The original river channel has been buried in localized areas by landslide debris. Currently, the river channel contains several long, slow pools that are backed up by short, steep cascades or rapids formed from landslide debris (photograph A-2). In addition to the reservoir-induced landslides, remnants of Linderman Dam and the submerged borrow pits upstream from Teton Dam have also impacted the predam slope of the river channel.

It was suspected that the number of pools increased as a result of the landslides, resulting in lower flow velocities and longer retention times of water flowing through the pools. This, in turn, could lead to warmer water temperatures in summer and fall and a greater potential to trap fine-grained sediment in pools.

The effects on wetland (Beddow, 1999) and upland (Beddow, in progress) habitats are being studied to determine what changes have occurred on the Teton River as a result of the Teton Dam Project. Studies involve assessing geologic, geomorphic, hydraulic, hydrologic (England, 1998), and temperature conditions (Bowser, 1999) in the reaches affected both upstream and downstream from the Teton Dam site.

Study Purpose and Objectives

The purpose of the study is to provide technical information to aid in managing Reclamation withdrawn lands in and around the Teton River canyon upstream from the Teton Dam site. The objectives of this study are to document the current physical conditions (geologic, geomorphic, and hydraulic) of the Teton River upstream from the dam site and changes that occurred from the filling of Teton Reservoir and subsequent failure of Teton Dam in 1976.


USGS
Gaging Station
(13055000)
Teton Dam Site
Canyon Creek
Linderman Dam
Spring Hollow
Bitch Creek
Badger Creek
Milk Creek
Felt Dam
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0 1 2 3 4 5 6 7 8 9 10 Miles

Section 2

Geologic History and Previous Studies

The geologic study area of the Teton River canyon is bounded between the Rocky Mountain overthrust and younger Snake River Plain downwarp (a downward bend on subsidence of a part of the earth's crust). The major geologic activities in the area are the uplift of the Teton and Snake River Ranges (the eastern extent of the Snake River Plain) and the associated volcanic activity from Island Park and the Yellowstone area. During the late Pliocene and early Pleistocene age (2.1 million years ago), the Huckleberry Ridge tuff, a 200- to 600-foot-thick flow of rhyolite from Yellowstone Caldera, was deposited over a pre-existing uneven landscape (Pierce and Morgan, 1992). The Teton River started downcutting through the rhyolite, likely due to uplifting of the Rexburg Bench in relation to the subsidence of the adjacent Snake River Plain to the west. Following incision of the Teton River into the Huckleberry Ridge tuff, a single younger basalt flow entered the Teton River canyon just downstream from the present dam site and flowed upstream, covering river gravel and filling the lower part of the canyon to a depth of about 125 feet (Magleby, 1968). The Teton River continued its active erosion cycle and extensively eroded the intracanyon basalt flow. The lower river near the dam site then changed from degradation to aggradation, resulting in the deposition of over 100 feet of sand and gravel, completely burying the remnants of the intracanyon basalt flow (Magleby, 1968).

Today, steep canyon walls typically rise 300 to 500 feet above the river in the nearly 17-mile-long reach upstream from Teton Dam that was inundated by Teton Reservoir. A 1972 contour map was developed that represents the Teton River and canyon prior to the filling of Teton Reservoir (Magleby, 1981). The water surface elevations from the 1972 contour map for 19 river miles upstream from the Teton Dam site were plotted to show the slope of the river prior to the filling of Teton Dam (figure 2). The 1972 water surface profile is based on 5-foot contours. At the upstream end (River mile (RM) 19), the Teton River canyon is narrow, resulting in a steep river slope. The canyon becomes gradually wider downstream, and the slope of the river decreases.

Typical of a river canyon widening process, the river will actively erode the toes of the canyon slopes and slope failures will occur, carrying large volumes of material to the canyon floor. Over time, the river will transport the smaller size material downstream, leaving larger boulders at the landslide areas. These large boulders often form riffles and pools that, in turn, form sediment traps for the development of islands and terraces along the river channel. There are numerous areas along the Teton River canyon walls where landslides historically constricted the river channel and created riffles and pools that can be seen on aerial photographs (appendix D). A landslide of this nature occurred between the confluences with Badger and Bitch Creeks (upstream from the former reservoir). This landslide caused a debris flow which constricted the river channel, forming a large rapid that is evident in the 1972 aerial photographs. Within the last several years, an additional landslide occurred at this location, enlarging the existing rapid. This rapid was noted during 1997 field work as being difficult to navigate due to the increased drop in water surface and large amounts of debris.

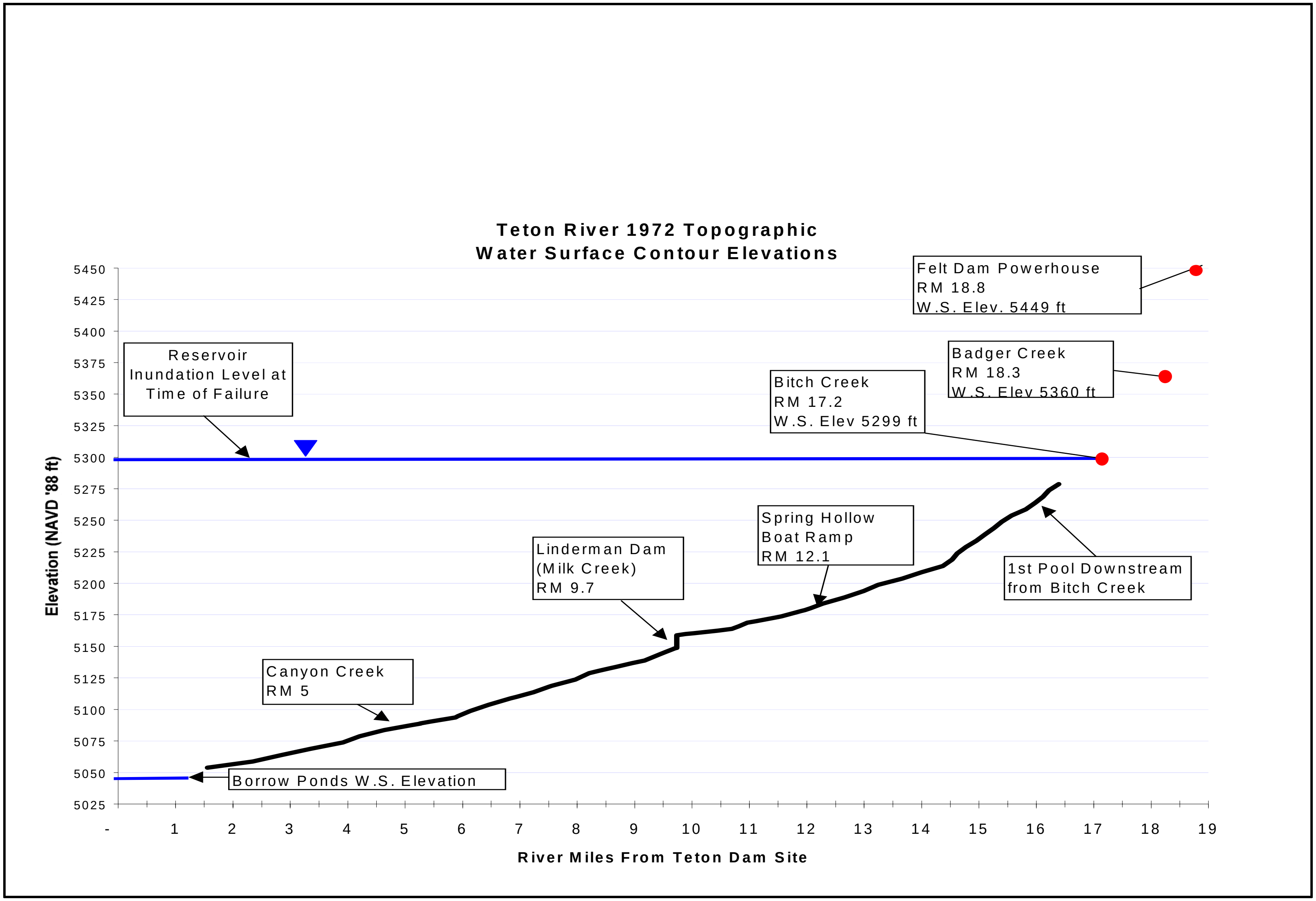

Figure 2.-Teton River orientation graph showing 1972 water surface elevation contours and the 1976 reservoir inundation reach.

Hundreds of landslides occurred along the canyon walls in 1976 during the filling and rapid drawdown of the reservoir (photograph A-5). The majority of the Teton River canyon in the reservoir area is oriented in an east-west direction. Most of the 1976 landslides were located along the south canyon walls, which are typically underlain by fine-grained sediment, as opposed to the wall on the north side, which is primarily bare bedrock.

1965 Reservoir Landslide Study

A preliminary landslide evaluation was conducted for the Fremont Reservoir site (former name for the Teton Dam and Reservoir), on the Teton River, by personnel from Reclamation's Pacific Northwest Regional Office (Magleby, 1965). The reservoir site was described as a rather steep-walled, narrow canyon eroded 300 to 500 feet into an eolian loess-covered upland. The canyon walls that would serve as the walls of the reservoir were composed of a massive to thinly laminated rhyolite and a welded ash-flow tuff. The north wall was very steep or vertical, and the south wall was less steep and composed of a poorly sorted mixture of talus, colluvium, and loess blown over the slope from the upper bench lands.

The conclusions from this evaluation were there was no strong evidence of recent landslide activity in the reservoir area, nor were there any apparent geologic conditions that would be conducive to landslides under a reservoir environment. However, based on the aerial photograph interpretation for this study, it is clear that landslides and rockfalls have been the dominant surficial process responsible for formation of the Teton River canyon over the last several hundred thousand years, and landslides and rockfills obviously occurred due to the inundation of the reservoir.

1976 Predam Failure Landslide Inspection

In May 1976, during the filling of the reservoir behind the uncompleted Teton Dam, personnel from the Pacific Northwest Regional Office performed a landslide inspection along the reservoir shoreline (Carter, 1976). The reservoir water surface was at elevation 5228.4 feet, about 95.9 feet below the maximum water surface of 5324.3 feet. Numerous landslides were observed that had developed in the loosely consolidated colluvial materials mantling the steep canyon walls.

Conspicuous slide scars and cracks were noted at 24 locations in the Teton River and the Canyon Creek arms of the reservoir (table 1). Most of the landslides varied in volume from 100 to 1,500 cubic yards. One large slide on the west slope of Canyon Creek was noted as involving an estimated 5,000 cubic yards. The thickness of the landslide was less than 15 feet at most locations.

The conclusions from this inspection were that, under reservoir filling conditions, shallow slides were to be expected on steep canyon slopes mantled with loosely consolidated colluvium. The landslides were predicted to continue until stable, in-place rock was encountered along the canyon wall. Because the vegetation was already cleared, shoreline erosion in the windblown

Table 1.—List of the landslides and their general location observed during May 1976

Type of landslide	Number observed	River miles from dam	Location on reservoir
Cracks and small slumps	minor	0 - 2.5	Teton Dam to Hog Hollow
Minor slide	1	2.5	Mouth of Hog Hollow, east slope
Slumps and minor slides	5	2.5 to 5	Hog Hollow to Canyon Creek, south rim
Scars, skin slides, large slide	4	5	Canyon Creek, west slope
Scars, cracks, skin slides	2	5	Canyon Creek, east slope
Minor slide	1	5 to 9.6	Canyon Creek to Milk Creek, south rim
Scars, cracks, slumps, minor slide	6	9.6 to 12	Milk Creek to Spring Hollow, south rim
Scars, cracks, skin slides	5	12 to approx.17	Upstream of Spring Hollow, south rim

Data taken from memorandum dated June 4, 1976, to Director of Design and Construction, E&R Center, from Regional Director, Boise, Idaho, Subject Field Inspection of Shallow Slides on Teton Reservoir, Teton Project, Idaho.

loess could occur along the reservoir rim. In some areas, the thickness of deep colluvium could be in excess of 75 feet. After these colluvial deposits became saturated under full reservoir conditions, larger landslides could develop during periods of drawdown.

June 5, 1976, Teton Dam Failure

On June 5, 1976, when the reservoir was at elevation 5301.7 feet, and during the initial filling of the reservoir, the dam failed catastrophically, releasing 250,000 acre-feet of water over a 6-hour period (Schuster and Embree, 1980). The rapid draining of the reservoir resulted in a large number of landslides on the formerly submerged, steep canyon wall slopes. For the most part, the unstable materials on the slopes were only a few feet thick and the sliding was mainly translational, often exposing bedrock at the rupture surface. In some locations, the colluvium was thicker and failed by slumping or a combination of slumping and translation. Locally along the rim, rockfalls and rock slides occurred in the welded tuff bed rock, but these failures were on a considerably smaller scale than failures in the loess and colluvium (Magleby, 1977). Slide activity was enhanced in both the unconsolidated materials and the bedrock by return of water from the saturated banks to the river after rapid drawdown of the reservoir (Magleby, 1977).

Landslide Interpretations on 1972 Base Map

Some of the landslides that were triggered by the dam failure have constricted the Teton River to a greater degree than historic conditions. In addition, a large amount of debris was deposited into the river channel that, combined with the constriction, created or enlarged existing riffles and rapids. These new or enlarged rapids have increased the elevation of the river pools and increased the drop in water surface through the riffles and rapids. A set of topographic maps were developed, which show landslide activity along the canyon walls prior to the dam failure, during the filling of the reservoir, and after the failure of the dam (Magleby, 1981). These maps were based on 1972 topographic contours developed from 1972 photography. Additional studies were conducted to estimate the quantity of landslide material erosion.

Estimation of the Quantity of Landslide Material

Estimating the amount of landslide debris that moved to the valley floor in the Teton River canyon is a difficult task because of limited field data available. Some estimates were based on the percentage of the slopes that failed, some were based on the volume of material, and some were based on both percentage of slope and volume of material. In each case, due to limited field mapping, an estimate of the average thickness of the slides had to be used (table 2). The estimated quantity of material that moved during the 1976 landslides ranged between 2.7×10^6 yd^3 and 4.3×10^6 yd^3.

Table 2.—Summary of 1976 landslide volume estimates

Estimator	Method	Teton River	Canyon Creek	Total volume
Pre-Failure				
Reclamation/ B.H. Carter, 1976	Volume estimate, based on field inspection	19,200 yd^3	5,000 yd^3	1.97×10^4 yds^3
Post-Failure				
Reclamation/ D. Magleby, 1977	Surface area (48.5×10^6 ft^2) field study	40% (16.8×10^6 ft^2), 16 miles	50% (6.3×10^6 ft^2), 2.5 miles	4.3×10^6 yds^3
Reclamation/ D. Magleby, 1979	Volume estimate, based on aerial photographs	550,000 ft^3 (large slides only or 21% of slides)	440,000 ft^3	2.6×10^6 yds^3+ 9.9×10^5 yds^3 = 3.59×10^6 yds^3
Reclamation/ D. Magleby, 1979	Surface area (total 15.99 miles for Teton River and 2.5 miles for Canyon Creek), based on aerial photographs	10.2 miles (63%), south rim; 3.1 miles (20%), north rim (42% for river)	1.59 miles (63%), left bank; 1.4 miles (56%), right bank) (60% for Canyon Creek)	2.7×10^6 yds^3
U.S. Geological Survey/ R. Schuster, 1980	Total surface area that could slide (1,460 acres), based on aerial photographs	337 acres, south rim; 91 acres, north rim	72 acres	3.6×10^6 yds^3

Section 3

Data Collection and Analyses

Data were collected in 1997, 1998, and 1999 along the Teton River between the Teton Dam site and the Felt Dam Powerhouse, 19 river miles upstream. The data collected consist of new aerial and ground photographs, measurements of riverbed topography, water surface elevations, and bed-material particle size distributions. Additional data were collected on water quality and the riparian vegetation community and are described in separate reports (Bowser, 1999; Beddow, 1999).

Pools are defined for this study as a portion of the river that has a water surface elevation controlled by a downstream feature (such as a riffle or rapid), has a relatively flat water surface with little or no slope, deep depths, and low velocities; and is in the subcritical flow regime. Riffles are defined for this study as a reach of river with high velocities and shallow depths that are in the critical flow regime. Rapids are defined for this study as a reach of river, typically constricted relative to upstream and downstream river widths, that passes through critical depth at the upstream end and creates a large drop in water surface elevation over a short distance. Chutes are defined for this study as a portion of the river containing a series of riffles.

Twenty-seven existing (1997-99) pools and 27 rapids (or riffles) along the Teton River, between the confluences with Bitch Creek and Canyon Creek, were surveyed. The pools and rapids (or riffles) were numbered in increasing order in the downstream direction. For example, the first pool downstream from Bitch Creek is labeled pool 1 (formed by riffle 1), and the first pool downstream from Spring Hollow is labeled pool 10 (formed by riffle 10). Pool 27, the last pool, is located upstream from rapid 27, which is the last rapid before the confluence with Canyon Creek. Below Canyon Creek, the river is relatively shallow, and no major pools exist, with the exception of the borrow ponds located from RM 1.5 to the Teton Dam site. The locations of all data collected are identified by river miles from the Teton Dam site in the upstream direction (figure 2).

Aerial Photographs

Historical aerial photographs of the Teton River canyon used for this study were taken in 1957, 1972 (Reclamation; scale: 1:9,600; black/white), 1976 (Reclamation; scale: 1:12,000; color), and 1977 (Reclamation; scale: 1:12,000; color). New photographs were taken for this study in 1997 (flown by Valley Air Photos on August 30, 1997, for Reclamation; scale: 1:1,000; color). The aerial photographs most extensively used for this report were the sets taken in 1972 (predam conditions) and 1997 (existing conditions). The flight for the 1997 aerial photographs was scheduled at a time to closely match the river discharge of the 1972 aerial photographs. The mean daily discharge recorded at the U.S. Geological Survey (USGS) gaging station near St. Anthony, Idaho, was 739 cubic feet per second during the 1972 flight and 725 cubic feet per second during the 1997 flight.

Ground Photographs

Ground photographs of the Teton River canyon were taken during field trips in July 1997, August 1997, July 1998, and June and July 1999 (appendix A). During the 1997 trips, photographs were taken between Felt Dam Powerhouse (RM 19) and the Teton Dam site (RM 0). During the 1998 trip, photographs were taken between the Felt Dam and the Teton Dam site.

During the 1999 trips, photographs were taken from along the canyon rim (June) and along the river between Bitch Creek and Spring Hollow (July).

River Channel Survey Data

The purposes of collecting river channel survey data were to document the existing river channel conditions upstream from the Teton Dam site and to evaluate the amount of change since the 1976 landslides. Hydrographic data defining the water surface and channel bottom and limited topography data were collected for four reaches of river between the upstream extent of the reservoir inundation at the confluence with Bitch Creek (RM 17.2) and the Teton Dam site:

1. **Bitch Creek (RM 17.2) to Spring Hollow (RM 12.1).—**The upstream survey reach was measured in July and September 1999 and extends from the first pool (RM 16) downstream from the confluence at Bitch Creek downstream to the road access at Spring Hollow. The survey data include longitudinal water surface profiles, transverse cross-section lines, and limited ground topography on bars and islands.

2. **Spring Hollow (RM 12.1) to Canyon Creek (RM 5).—**The second survey reach was measured in 1997 and extends for 7 miles downstream from the road access at Spring Hollow (in Section 11, T. 7 N., R. 43 E.) to just downstream from the last large rapid, approximately 0.2 mile upstream from Canyon Creek (in Section 24, T. 7 N., R. 42. E.). The survey data include longitudinal water surface profiles; transverse cross-section lines; edge of water measurements through the pools, rapids, and Linderman Dam; and limited canyon topography. Some additional cross sections were measured in 1998 in this reach to fill in gaps where data were missing.

3. **RM 4.—**The third survey reach, which is relatively short (800 feet long), was surveyed in 1998. This reach is located about 1 mile downstream from Canyon Creek, at RM 4.0. The survey data include six transverse cross-section lines of the river channel and an old, high terrace on the north (right) side of the river (photograph A-18).

4. **Borrow Ponds (RM 1.5 to the Teton Dam Site).—**The fourth, and most downstream, survey reach was measured in 1997 and is known as the borrow ponds reach. The borrow ponds are submerged borrow pits that were used to supply materials for the construction of Teton Dam. The borrow ponds consist of two deep pools and a parallel river channel that can bypass a portion of flow around the downstream pond (photograph A-15). The survey data include longitudinal water surface profiles, transverse cross-section lines, edge of water measurements, and limited ground topography on the berms.

The hydrographic survey data were collected using a raft equipped with a depth sounder to measure the channel bottom through each pool, while a total station survey instrument recorded the water surface elevation and horizontal position at each measurement. (See photographs A-13 and A-14 and appendix C for more detail on survey methodology.) Survey lines consisted of cross sections perpendicular to flow, longitudinal or diagonal lines, and edge of water points.

To check the accuracy of the survey, the vertical coordinates of the 1997 Spring Hollow to Canyon Creek survey data were plotted by river mile (figure 3). In contrast to field observations of relatively flat pools that dropped slightly in elevation in the downstream direction, measured water surface elevations through pools tended to rise slightly in the downstream direction, and fluctuated up to ± 1 foot across any transverse line in a pool. This measurement error was due to the limitations of the instrument and the difficulty in tracking the moving raft, thus limiting the vertical precision of the survey measurement. This vertical error was corrected for calibration purposes by determining the average water surface elevation across each pool to eliminate the vertical fluctuations. The vertical coordinates of the 1999 Bitch Creek to Spring Hollow survey data were also plotted by river mile (figure 4). A new survey instrument used in this reach eliminated the ±1-foot fluctuations caused by the previous survey instrument.

The major focus of this study was in the river reach between the confluence with Bitch Creek and the confluence with Canyon Creek. The pool nomenclature, river mile location of each pool, pool length, mean pool elevation used for calibration, and the estimated drop through each rapid for this river reach were documented (tables 3 and 4). In addition, six cross sections were surveyed at RM 4 (downstream of Canyon Creek), representing the channel bottom and right overbank topography. The water surface elevation measured at the upstream end of this reach was approximately 5077 feet with a 2-foot drop in water surface elevation through the riffle. Just upstream from Teton Dam, 24 cross sections perpendicular to flow were measured in the 2 borrow ponds, in addition to longitudinal survey lines. The borrow ponds are a fairly level reach of river, with an average water surface elevation at approximately 5046 feet. Additional data were also measured in the diversion channel parallel to the downstream borrow pond.

Table 3.—Summary of existing conditions (1999) survey data corresponding to a discharge of 670 ft^3/s (RM 16.1 to 12.1)

Teton River section	River mile from Teton Dam site	Length of pool (ft)	Mean measured pool elevation (NAVD '88 ft)	Estimated drop in water surface to next pool (ft)
Felt Dam	19.1			
Badger Creek	18.5			
Bitch Creek	17.4			
Pool 1	16.1087 to 16.0599	260	5264.0	5.0 (rapid 1)
Cobble bars	16.0085 to 15.9195	470	5259.0	2.0 (riffle 1)
Pool 2	15.8365 to 15.5791	1,360	5257.0	13.5 (rapid 2)
Pool 3	15.3916 to 14.9399	2,390	5243.5	11.0 (rapid 3)
Pool 4	14.8452 to 14.0832	4,020	5232.5	16.0 (rapid 4)
Pool 5	13.7408 to 13.2138	2,780	5216.5	8.5 (rapid 5)
Pool 6	13.1191 to 12.7642	1,870	5208.0	6.0 (rapid 6)
Pool 6b	12.6802 to 12.6684	60	5202.0	3.0 (riffle 6)
Pool 7	12.5854 to 12.4525	700	5199.0	4.0 (rapid 7)
Pool 8	12.3613 to 12.2624	520	5195.5	2.5 (rapid 8)
Pool 9	12.2333 to 12.1341	520	5193.0	4.0 (rapid 9)

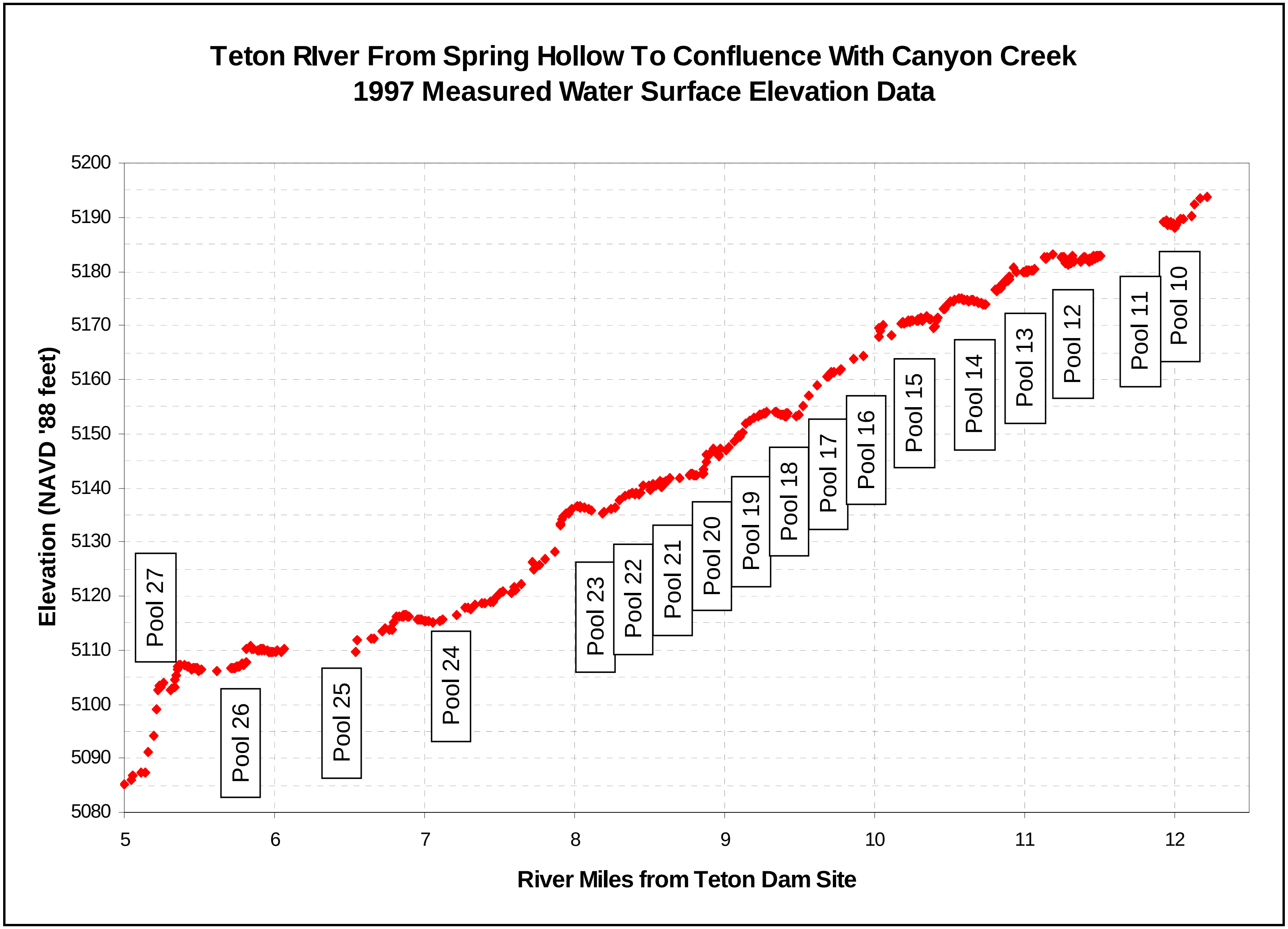

Figure 3.—Measured (1997) water surface profile for Teton River from Spring Hollow to confluence with Canyon Creek.

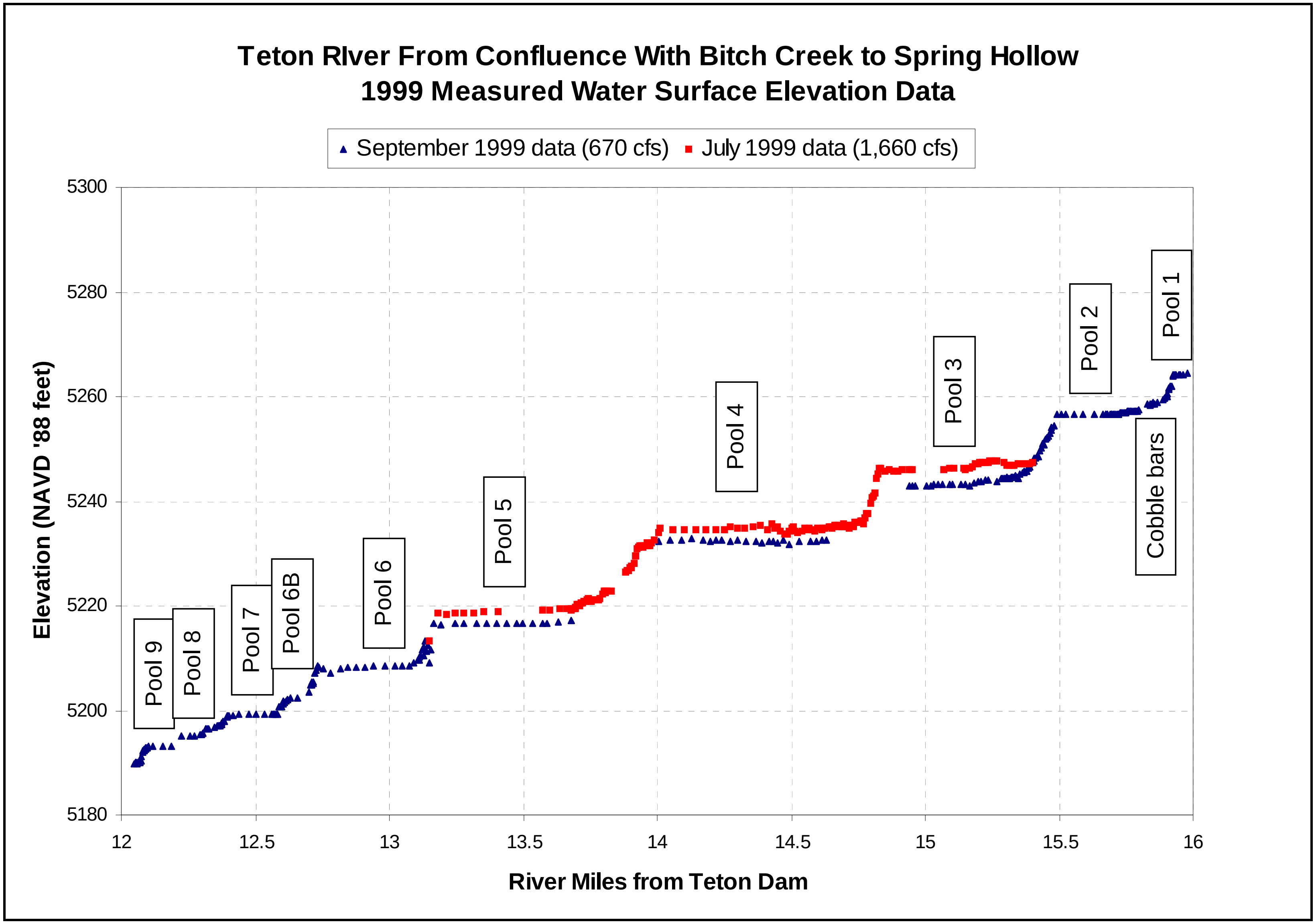

Figure 4.—Measured (1999) water surface profile for Teton River from confluence with Bitch Creek to Spring Hollow.

Table 4.—Summary of existing conditions (1997-98) survey data corresponding to a discharge of 1,400 ft³/s (RM 12.1 to 5.0)

Teton River section	River mile from Teton Dam site	Length of pool (ft)	Mean measured pool elevation (NAVD) 88 ft	Estimated drop in water surface to next pool (ft)
Spring Hollow	12.100			
Pool 10	12.063 to 11.917	770	5189.0	2.0 (riffle 10)
Pool 11	11.898 to 11.517	2,010	5187.0	4.5 (rapid 11)
Pool 12	11.504 to 11.136	1,940	5182.5	2.5 (rapid 12)
Pool 13	11.117 to 10.909	1,100	5180.0	5.5 (rapid 13)
Pool 14	10.814 to 10.492	1,700	5174.5	4.0 (rapid 14)
Pool 15	10.445 to 10.165	1,480	5170.5	6.5 (rapid 15)
Pool 16	10.032 to 9.903	680	5164.0	2.5 (rapid 16)
Pool 17	9.884 to 9.734	790	5161.5	2.0 (dam)
Linderman Dam	9.734			
Pool 18	9.722 to 9.623	520	5159.5	6.0 (rapid 18)
Pool 19	9.537 to 9.158	2,010	5153.5	7.0 (rapid 19)
Pool 20	9.063 to 8.978	450	5146.5	5.0 (rapid 20)
Pool 21	8.959 to 8.618	1,800	5141.5	2.5 (rapid 21)
Pool 22	8.552 to 8.414	730	5139.0	3.5 (rapid 22)
Pool 23	8.395 to 8.112	1,500	5135.5	3.5 (rapid 23)
Chute of riffles	7.979 to 7.502	2,100		16.0 (chute)
Pool 24	7.502 to 6.962	2,850	5116.0	5.5 (rapid 24)
Pool 25	6.943 to 5.956	5,220	5110.5	4.0 (rapid 25)
Pool 26	5.918 to 5.471	2,360	5106.5	3.0 (rapid 26)
Pool 27	5.442 to 5.347	500	5103.5	16.0 (rapid 27)
Canyon Creek	5.000		5087.5	

Bathymetric Maps

The existing channel topography data, collected in 1997-99, was used to create a set of bathymetric maps for the Teton River pools from the confluence with Bitch Creek to the confluence with Canyon Creek and in the borrow ponds just upstream of the Teton Dam site (appendix J). The maps were developed using a Geographic Information System (GIS) package that develops contours based on individual data points. Each pool has color-coded depths that represent the depth of the water corresponding to the discharge at the time the data was surveyed. The maps document: (1) the location of the measured data used to develop the maps; (2) the average daily discharge recorded at the time of the survey; (3) the mean measured water surface elevation of each pool during the survey; and (4) the locations of cross sections used in the hydraulic model for this study. The edge of water, or boundary line, for each pool was estimated based on measured data and 1997 aerial photograph analysis. Bathymetric data through each rapid was too difficult to measure; however, the length of each rapid is approximately correct on the maps. Note that in areas where there was little or no measured data, contours were not generated.

Bed-Material Particle Size Data

Bed-material sampling of river pools was collected by the U.S. Geological Survey during a separate field trip in August 1997, when the flow rate was 725 cubic feet per second. This low flow corresponded to low turbidity, which provided visibility of the riverbed at greater depths (Jacobson, 1998). Hydrolab measurements were also documented. Samples were identified by two numbers; the first number is the pool number where the sample was taken, and the second number, which increases in the downstream direction, is the sample number in that pool. The horizontal location of the samples was recorded using a hand-held Global Positioning System (GPS). Maximum particle size measurements may have been limited by sampling equipment and methodology. Bed-material samples were analyzed in the laboratory for particle-size gradations. Appendix B contains the particle-size gradations for each pool referenced to the same pool numbers used in this report.

Landslide-Material Particle Size Data

Prior to 1998, very little work had been completed on determining the size of material in the landslide debris along the Teton River. Magleby used a helicopter, in April 1977, to make some rough estimates on the size of material in the landslides along the river. Several landings were made in the canyon. Five to 25 percent of the slide debris was estimated to be composed of silt to sand-sized material. The remainder was composed of gravel-size and boulder-size blocks of rock up to 5 feet across, with the predominant size ranging from gravel to boulders 3 feet in diameter. During the 1998 field investigations, size estimates of the landslide debris covering the valley floor were made by two methods at seven sites along the river (tables 5 and 6).

Table 5.—Site locations of landslide material sampling

Site number and name	Location	Type of slide
1. Between Badger and Bitch Creeks (this slide occurred in 1997)	T. 7 N., R. 44 E., Sec. 20, SW 1/4	Shallow debris slide, mostly rock in chute, south rim
2. About 3/4 mile downstream of Spring Hollow (rapid 11)	T. 7 N., R. 43 E., Sec. 10, SE 1/4	Rock debris slide, north rim
3. Third rapid below Linderman Dam (rapid 20)	T. 7 N., R. 43 E., Sec. 21, NW 1/4	Shallow slump and earth flow, south rim
4. Madison County line (Rapid 21)	T. 7 N., R. 43 E., Sec. 20, SW 1/4	Shallow earth flow, south rim
5. Little Parkinson's Rapid (rapid 26)	T. 7 N., R. 42 E., Sec. 24, SW 1/4	Rock debris slide, north rim
6. Parkinson's Rapid (rapid 27)	T. 7 N., R. 42 E., Sec. 24, SW 1/4	Shallow slump and earth flow, south rim
7. Big Terrace, 3/4 mile downstream of Canyon Creek	T. 7 N., R. 43 E., Sec. 23, NW 1/4	Shallow sump and earth flow, south rim

Table 6.—Gradation system used for landslide debris fans

Fines to gravel	Cobbles	Small boulders	Medium boulders	Large boulders
Clay/silt sand to 3" gravel	3" to 12" rock fragments	1.0' to 3.0' rock	3.0' to 10.0' rock	> 10'

The first method was a random estimate made by walking a portion of a landslide and selecting at random an area about 50 feet square (photographs A-8, A-26, A-27, A-43; table 7). A surface count or percentage estimate was made of the various sizes of material exposed in the square. Five of the sites (sites 1 through 5) represent random estimates.

Table 7.—Random counts or percentage estimates made at the five random sites along the Teton River

Site number	Fines (clay, silt, sand)	Cobbles	Small boulders	Medium boulders	Large boulders
No. 1	5%	30%	40%	20%	5%
No. 2	15%	35%	30%	15%	5%
No. 3	30%	40%	20%	10%	0%
No. 4	20%	45%	20%	10%	5%
No. 5	15%	40%	30%	10%	5%
Average	17%	38%	28%	13%	4%

50- by 50-foot square = 2,500 ft^2 for each site.

The second method was to select an area 100 feet by 100 feet; then divide that area into quarters, making a grid system consisting of four 50- by 50-foot grids (table 8). A surface count was made of exposed materials in each of the four 50- by 50-foot grids (photograph A-24). Two of the sites (6 and 7) were used to make grid counts. Two separate grid counts were conducted at the two sites, and the grids were separated by about 200 feet. Material less than 3 inches in diameter had to be estimated as a percentage of the total surface material exposed.

Table 8.—Four grid counts made at two landslide sites along the Teton River

Site number	Fines (clay, silt, sand)	Cobbles	Small boulders	Medium boulders	Large boulders
No. 6 (A)	40%	50%	5%	4%	1%
No. 6 (B)	40%	45%	7%	7%	1%
No. 7 (A)	45%	45%	2%	7%	1%
No. 7 (B)	50%	44%	3%	2%	1%
Average	44%	46%	4%	5%	1%

100- by 100-foot square = 10,000 ft^2 for each site.

The estimates indicate that the predominant sediment sizes in the landslides along the Teton River range from cobbles to small boulders (3 inches to 3 feet, photographs A-7 and A-38). The second largest size is the fines to 3 inches, with medium and large boulders making up the smallest percentage (photographs A-8, A-9, and A-26).

This range of material sizes appears to be consistent with the material described for the slopes of the Teton River canyon prior to the construction of the dam. In the 1968 preliminary geologic report of the Teton Dam site (Magleby, 1968), the canyon sides were noted as being covered with talus and colluvium varying from 0 foot to 10 feet thick (photographs A-6, A-7, and A-38). The colluvium is a loosely compacted, poorly sorted mixture of sand- to cobble-size fragments of rhyolite in a silty matrix; the talus is composed of elongated fragments of rhyolite up to 2 feet across. Drilling of the rhyolite along the Teton River canyon indicates that the fracture and joint spacing in the rock ranged from 0.2 foot to 3.0 feet (Magleby, 1968).

Landslide Interpretations on 2000 Base Map

A previous study on landslide interpretations displayed all landslides on top of contours developed in 1972 prior to the failure of Teton Dam (Magleby, 1981). While the 1972 base map worked well for displaying predam landslide interpretations, it did not work well for displaying postfailure interpretations because after the dam failure, the topography in the canyon was altered significantly. Further, additional interpretations of the landslides were done in 1997-98 as part of this study to look at the changes that occurred since the dam failure. To provide a new base map that represents existing topography in the canyon, a set of contour maps based on 2000 aerial photography is anticipated to be developed by the end of the year. This new 2000 base map will allow existing conditions interpretations and data to be presented on existing conditions topography while the predam interpretations will remain on the 1972 base map. The interpretations for this map will be presented directly on the 2000 base map; therefore, a separate report will be generated.

Section 4

Geomorphic Interpretation

The inundation by the reservoir and the rapid drawdown following the failure of Teton Dam had a significant impact on the geomorphology of the Teton River canyon. Along portions of the 17-mile-long reservoir, landslides and rock falls from the canyon walls locally blocked or deflected the course of the river. The largest impacts from the dam failure on geomorphic conditions occurred between the first pool downstream of the confluence with Bitch Creek downstream to the confluence with Canyon Creek. Landslides downstream from Canyon Creek largely failed onto terrace surfaces and had minimal impact on the river channel.

To evaluate the changes and impacts on the river canyon geomorphology since the dam failure, aerial photographs were examined that were taken prior to the construction of the dam (1957 and 1972), immediately following the failure of the dam (1976 and 1977), and 21 years after the dam failure (1997). The geomorphic interpretation was combined with detailed channel bottom surveys of the existing conditions in the reach of the canyon just downstream from the confluence with Bitch Creek (RM 16.1) to just upstream of the confluence with Canyon Creek (RM 5.0) to identify the extent of the impact of the Teton Dam failure. In the Spring Hollow to Canyon Creek reach, channel bottom surveys and cross-sectional data were collected, during August 1997 and July 1998, when the flow was approximately 1,400 cubic feet per second (appendix E, plots E-77 to E-147). In this river reach, several larger landslides and rockfalls have created new rapids in the canyon, but they generally occurred at the same locations as previously existing rapids, large riffles, channel constrictions, midchannel bars, or islands. Pool elevations behind these newly created rapids appear to be elevated (on the order of several feet), based on field observations, aerial photography comparisons, and cross-section analysis.

Channel bottom surveys and cross-sectional data were also collected from the confluence with Bitch Creek downstream to Spring Hollow (during July and September 1999), when the flow was approximately 1,660 cubic feet per second and 670 cubic feet per second, respectively (appendix E, plots E-1 to E-76). Field observations made during July 1998 and 1999, and analysis of aerial photographs, indicate that the geomorphology impacts appear to be similar to impacts in the upstream-most section of the Spring Hollow to Canyon Creek reach (RM 12.1 to 8). In addition, the three upstream-most pools in this reach (pools 1 to 3) have filled to capacity with sediment. No impacts from the reservoir occurred in the reach upstream from Bitch Creek, the maximum extent of the reservoir at the time of dam failure.

Teton River From Felt Dam to Bitch Creek (RM 18.8, elevation 5449 feet, to RM 17.2, elevation 5299 feet; reach length = 1.6 miles (8,700 feet))

The Felt Dam to Bitch Creek reach is the narrowest and steepest section of the river in the study area. This reach is characterized by a sequence of long riffles and short pools. The average gradient through this 1.6-mile reach is about 91 feet per mile (0.017 ft/ft). Badger Creek is the only large tributary to the Teton River in this reach of the canyon. This reach was not inundated by the reservoir and, therefore, was not affected by the dam failure. The bathymetry in this reach was not surveyed, so the details of the river channel topography are not known.

During field reconnaissance in July 1998, a large debris flow was observed on the left side of the canyon (looking downstream) between Badger and Bitch Creeks (photographs A-41, A-42, and A-43). According to biologists working on the river, this debris flow occurred sometime during the last several years. The resulting debris enlarged a previously existing rapid, thus further constricting the river channel. The slide and large rapid at this site provide a good illustration of the naturally occurring, mass-wasting processes inherent in the continuing evolution of the Teton River canyon.

Teton River From Bitch Creek to Spring Hollow (RM 17.2, elevation 5299 feet, to RM 12.1, elevation 5190 feet; reach length = 5.1 miles (27,000 feet))

The reach of the river from Bitch Creek to Spring Hollow is also relatively narrow. Long riffles and short pools are common (photograph A-39). The average gradient through this 5.1-mile reach is about 21 feet per mile (0.004). Bitch Creek is the only large tributary in this reach of the Teton River and marks the upstream extent of inundation by the reservoir. The part of the canyon where the effects of the dam failure are readily apparent begins about 1 mile downstream from the confluence with Bitch Creek. The river in this part of the canyon currently contains nine pools and rapids that were either created by, or enlarged by, the landslides associated with the inundation of the reservoir and/or the failure of the dam. Prior to the Teton Dam, three riffles (2, 3, and 4) existed in the upstream part of this reach of the river. Landslides triggered by the reservoir enlarged each of the existing riffles. A small rapid (near rapid 1) existed prior to the dam and is now inundated by a pool backed up behind a new rapid of similar size just downstream. Field observations show that the first three pools have short travel time, high velocities, and have filled to storage capacity and, therefore, cannot store any additional sediment transported by the river. The majority of sediment sizes visible in pools 1, 2, and 3 are fine grained (silt, clay, and sand) with a few cobbles present.

Much of the debris associated with these slides has been significantly modified by the river during the last 21 years. The channel at each of these sites is constricted to a greater extent than prior to the dam failure, but transport of the finer material in the slides has built new bars and islands downstream. Prior to the dam failure, the channel in the lower part of the reach contained abundant boulders that created long riffles. In addition, the channel contained numerous islands or midchannel bars. The channel was commonly very narrow in reaches, but was generally free of larger rapids. Five new rapids were created in this reach as a result of large landslides. The origin of each landslide that created the existing rapid and the conditions prior to the 1976 dam failure are listed in table 9.

Table 9.—Landslide origin of each rapid and 1972 conditions for Bitch Creek to Spring Hollow

Rapid Number	Landslide Origin	1972 Channel Conditions
1 (rapid)	Left canyon wall	Rapid existed upstream, now inundated by pool 1
1 (riffle)	Left canyon wall	Riffle existed
2 (rapid)	Both canyon walls, primarily from the right side	Riffle existed, was significantly enlarged by new slide
3 (rapid)	Left canyon wall	Riffle existed, was significantly enlarged by large slide
4 (rapid)	Left canyon wall	Several small riffles were present in the reach and the channel constricted by debris at small side canyons
5 (rapid)	Left canyon wall	Narrow channel, small riffle; channel constricted by debris from small side canyons on both canyon walls
6 (rapid)	Left canyon wall	Channel relatively narrow; contained large vegetated island just upstream of present rapid
6 (riffle)	Right canyon wall	Relatively wide channel with several large boulders in the center of the channel
7 (rapid)	Both canyon walls	Shallow riffle, enlarged by large slides
8 (rapid)	Both canyon walls, primarily from the left side	Relatively wide channel; small vegetated island along the right side of the channel
9 (rapid)	Left canyon wall	Wide shallow channel with vegetated island, landslide forming new rapid forced main channel to the right side of the canyon

Teton River From Spring Hollow to Canyon Creek (RM 12.1, elevation 5190 feet, to RM 5, elevation 5085 feet; reach length = 7.1 miles (37,000 feet))

The reach of the Teton River canyon from Spring Hollow to Canyon Creek is slightly wider than the reaches upstream, but is still very narrow compared to the reach downstream from Canyon Creek. The average gradient through the reach is about 15 feet per mile (0.003). Prior to dam construction, the channel in this reach was flanked by a narrow flood plain and low terraces. The upper 4 miles of the reach (RM 8 to 12) were characterized by a series of low riffles and deep pools. The lower 3 miles of the reach (RM 5 to 8) had a locally steep gradient that was marked by long riffles and midchannel bars and shorter pools, very similar to the present reach between Felt Dam and Bitch Creek.

A total of 18 pools and rapids now exist within this reach (appendix K). Many of these rapids were newly created by the landslides and rockfalls produced by the reservoir inundation and dam failure. In some locations, new landslide debris either enlarged previously existing riffles or blocked a channel containing previously existing midchannel bars or islands. The hydraulic drop created by each of these rapids ranges from 2 to 16 feet (table 3). The greatest change in the river channel profile is in the lower 2 miles (RM 5 to 7), where landslide debris created new rapids that have raised the water surface by over 10 feet. The origin of each landslide that created the existing rapids and an interpretation of the 1972 conditions prior to the 1976 dam failure (table 10) were documented.

Table 10.—Landslide origin of each rapid and 1972 conditions for Spring Hollow to Canyon Creek

Rapid number	Landslide origin	1972 channel conditions prior to Teton Dam
10 (riffle)	Right canyon wall	No evidence of constriction
11 (rapid)	Both canyon walls	Riffle, landslide scar on right, large boulders in channel
12 (rapid)	Left canyon wall	Riffle, boulders in channel
13 (rapid)	Left canyon wall and remobilized ancient slide	Midchannel bar, scattered boulders in channel, rockfalls on right canyon wall
14 (rapid)	Both canyon walls, primarily from the left side	No evidence of constriction
15 (rapid)	Left canyon wall	No evidence of constriction
16 (rapid)	Left canyon wall	No evidence of constriction
17 (dam)	Linderman Dam	Hydraulic drop of 10 feet created by dam
18 (rapid)	Left canyon wall	Minor riffle
19 and 20 (riffles)	Left canyon wall	Midchannel bar, rock debris along right canyon wall
21 (rapid)	Both canyon walls	Few boulders in channel upstream of current rapid location, no evidence of constriction
22 (rapid)	Left canyon wall	Three midchannel bars and boulders evident in channel
23 (rapid)	Left canyon wall	Series of shallow riffles
Chute of riffles	No landslides	Series of riffles similar to 1997 conditions
24 (rapid)	Left canyon wall	Small riffle evident
25 (rapid)	Left canyon wall	Several riffles evident
26 (rapid)	Right canyon wall, small amount from left side	Riffle, large longitudinal island just downstream
27 (rapid)	Left canyon wall	Steep riffles evident; large longitudinal islands downstream

Along the entire 7.1-mile length of this reach, landslides and rockfalls are ubiquitous, but most have been subsequently modified or originally had a minimal impact on the channel. Many of the slides in the reservoir basin of Teton Dam were limited in their extent to the surfaces of the narrow flood plain, on the broader terrace surfaces, or along the canyon walls. Slides originating on the south-facing slopes primarily consist of rockfalls or shallow translational slides (photographs A-6 and A-7). The largest slides in this reach almost exclusively originated on the northerly facing canyon walls and typically blocked or deflected the channel. These slides moved large volumes of debris from the canyon walls to the canyon floor, where it was made available for transport by the river during higher flows. The dramatic increase in available sediment thus indirectly impacted the channel elevation and pool depths. Analysis of the 1976, 1977, and 1997 aerial photography indicates that these slides were subsequently overtopped and have been substantially eroded in the years since the dam failure. However, the rapids that persist in the canyon today are composed of debris from these slides.

The lateral extent and depth of each slide in the canyon can be directly related to the mean grain size and total volume of material that was available on the canyon wall at any given site. Deposits preserved along the south-facing slopes typically consist of steep talus cones and rockfalls (photographs A-12, A-21). Conversely, the north-facing slopes in many places are blanketed by thick colluvium and very well-developed, fine-grained soils formed in loess derived from the canyon rim (photographs A-5, A-11). The development of soil on these slopes is enhanced by the finer-grained character of the parent material, greater available moisture, and corresponding vegetation relative to the south-facing slopes. In a natural setting, this side of the canyon would be relatively more stable than the south-facing canyon wall because the north-facing slopes are more gentle, the soils are thicker, and the vegetation is denser (photograph A-2). However, because of the character of the deposits on the north-facing slopes, when they were inundated by the reservoir, they formed larger slides. In contrast, Canyon Creek was also severely impacted by landslides caused by the dam failure, but these landslides have not been modified to the same extent as landslide debris along the Teton River. Canyon Creek is a lot narrower and the gradient is steeper, on average, than the Teton River, but the drainage basin area, type of flows, and peak discharges are much less than those on the Teton River.

Linderman Dam

Linderman Dam was constructed across the Teton River at the confluence with Milk Creek sometime between 1957 and 1972 (based on analysis of aerial photographs). The right abutment of the dam is in volcanic rock forming the vertical canyon wall; the left abutment and much of the foundation is on the Milk Creek alluvial fan-delta. The fan-delta, formed at the mouth of Milk Creek, has forced the river along the north (right) side of the canyon and has constricted the river channel. This channel configuration certainly existed at this location for many thousands of years prior to the dam construction. A large pool (measured in 1997) with a maximum depth of 27 feet along the right side of the channel immediately downstream from the remnant dam supports this interpretation.

Based on contour elevations from the 1972 Teton Reservoir basin topographic map, the hydraulic drop across Linderman Dam (while in operation) was 10 feet. This drop formed a pool that backed up water 3,600 feet upstream, through the current locations of pools 15, 16, and 17. In 1972, the water surface elevation just upstream from Linderman Dam was approximately 5165 feet (at a discharge of 1,000 cubic feet per second). Due to the construction of Teton Dam and Reservoir, the operation of Linderman Dam was stopped, and portions of the dam were removed.

Linderman Dam is now partially breached, and the average water surface elevation just upstream from the dam is 5161 feet (at a discharge of 1,000 cubic feet per second). This indicates that the water surface elevation just upstream from Linderman Dam is about 4 feet lower today than in 1972 (see figure 7 in next section of report). The current hydraulic drop through Linderman Dam is only 2 feet. If the dam created a hydraulic drop of 10 feet in 1972, the upstream water surface is now 4 feet lower than in 1972, and the current drop is only 2 feet. Four feet of drop still needs to be accounted for to match 1972 conditions. This suggests that rapid 18, the first rapid downstream from Linderman Dam, has increased the elevation of the pool downstream of Linderman Dam (pool 18) by 3.5 feet from the 1972 conditions.

The structural remnants of Linderman Dam are composed of concrete that is eroded and vertical pipes within the dam that are exposed and protrude into the flow (photograph A-32). Also, a horizontal concrete beam in the center of the dam still extends across the river at about the level of the water surface (photographs A-31, A-32). At lower flows, the water surface is just below the bottom edge of the concrete beam. The beam is at least partially inundated at higher flows. Even though the beam may extend across a portion of the water surface, the water velocities under the beam would be high and pose a hazard to boaters on the river.

Teton River From Canyon Creek to the Borrow Ponds (RM 5 to RM 1.5)

The river through this 3.5-mile reach is significantly wider than it is through the upstream reaches. The channel consists of a sequence of short riffles and long, shallow pools that meander between broad, flat terraces (photograph A-18). The physical setting in the river canyon through this reach today is about the same as it was prior to the construction of Teton Dam. Even though several landslides occurred in this reach due to dam failure in 1976, the debris from these slides is primarily limited to the surface of adjacent terraces and did not reach the river. No major rapids were formed in the main channel in this reach of river. The only exception to this generalization is at the upstream end of the reach, where two very extensive landslides impinged on the channel. Both slides occurred on the northerly facing canyon slope at sites of previous ancient slides.

Teton River Through the Borrow Ponds Just Upstream From the Teton Dam Site (RM 1.5 to RM 0.4, elevation 5046 feet; reach length = 1.1 miles (5,800 feet))

The river through this reach prior to dam construction was characterized by a meandering channel and broad, flat terraces. The gravel terraces were used for construction material in the dam. The borrow pits excavated during construction of Teton Dam create two deep pools connected by a narrow channel (photograph A-15). The downstream pool has a maximum depth of 43 feet and a maximum top width of 380 feet. The upstream pool has a maximum depth of 36 feet and a maximum top width of 760 feet. The downstream pool is partially divided by a narrow berm. A narrow side channel that contains a portion of the flow runs parallel to the borrow ponds along the right side of the canyon. This diversion channel was used to bypass water around the downstream pool during the construction of Teton Dam. Together, the borrow ponds contain a total volume of about 1,000 acre-feet (1.6 million cubic yards).

Section 5

Hydraulic Modeling and Analysis of the Teton River Channel

A computer model was used to predict hydraulic properties (water surface elevation, depth, mean velocity, and travel time of water) along the Teton River canyon. The U.S. Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS) model (version 2.2, Brunner, 1997) was applied to four reaches:

1. The Teton River from Bitch Creek to Spring Hollow, RM 16.1 to 12.1, both predam (1972) and existing conditions (1999).

2. The Teton River from Spring Hollow to Canyon Creek, RM 12.1 to 5.0, both predam (1972) and existing (1997-98) conditions.

3. A short reach of the Teton River below Canyon Creek at RM 4, existing conditions (1998).

4. The borrow ponds, RM 1.5 to 0.4, existing conditions (1997).

In addition to modeling existing conditions, the predam channel hydraulics between Bitch Creek and Canyon Creek were also modeled based on estimated predam channel geometry. Comparisons between predam and existing hydraulic properties and channel capacity were made based on the model results. River miles (RM) upstream from Teton Dam were used to identify the locations of cross-section lines and rapids within each modeled reach to provide a consistent method of identification. The bathymetric maps provided as an attachment to this report show the locations of all cross sections developed for modeling (appendix J).

Hydraulic Model

The HEC-RAS model performs water surface profile and other hydraulic calculations for one-dimensional steady flow. The model predicts river stage and other hydraulic properties at each cross section along the river and for any specified discharge. The steady flow component of the HEC-RAS model is capable of modeling subcritical, critical, supercritical, and mixed-flow regimes. Along the 17 river miles of the Teton River being studied, a combination of pools, riffles, chutes, and rapids exists. For this study, the model was forced to work in the subcritical and critical flow regimes. Supercritical flow does occur within localized areas of the rapids, but not as an average condition across the rapid or between cross sections. Therefore, the detailed hydraulics within each rapid are beyond the scope of this study.

Several types of coefficients are used in the HEC-RAS model to determine energy losses. Friction losses associated with roughness are set using the Manning's n value. Manning's n values are determined based on the channel bed roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstructions, size and shape of the river channel, stage and discharge, seasonal change, temperature, and suspended material and bedload.

Discharges presented in the hydrologic analysis (England, 1999) were used in the model to evaluate hydraulic properties of flood peaks for the 2, 5, 10, 25, 50, and 100-year floods, and the median flows for May, June, July, August, and September. These flow values (table 11) were based on USGS gaging station data from the Teton River gage site near St. Anthony, Idaho (Gage Station No. 13055000).

Table 11.—Discharges used in hydraulic model simulations

Teton River near St. Anthony, Idaho		
Discharge (ft^3/s)	Description	
660	Discharge at which 1999 survey data were measured between Bitch Creek and Spring Hollow	
725	Discharge at which 1997 aerial photographs were taken	
739	Discharge at which 1972 aerial photographs were taken	
1,000	Typical summer discharge	
1,200	Discharge at which 1997 survey data were measured in the borrow ponds	
1,400	Discharge at which 1997 survey data were measured between Spring Hollow and Canyon Creek	
Peak discharge flood frequency estimates		
Peak discharge (ft^3/s)	Return period (years)	Annual exceedance probability (%)
3,440	2	50
4,680	5	20
5,430	10	10
6,280	25	4
6,860	50	2
7,410	100	1
Median (50-percent exceedance) discharges for summer months based on mean daily flows		
Discharge (ft^3/s)	Month	
1,430	May	
1,910	June	
1,060	July	
742	August	
629	September	

Teton River from Bitch Creek to Canyon Creek (RM 16.1 to 5)

Existing Conditions (1997-99) Hydraulic Model

The HEC-RAS model was applied to the entire reach of the Teton River from just downstream of the confluence with Bitch Creek to Canyon Creek to create an existing conditions (1997-99) hydraulic model. Survey data (1997-99), field observations (1998-99) and aerial photographs (1997) were used to develop the existing conditions model. Twenty-seven pools were identified in this reach (pool 6 has two parts - A and B). The pools are numbered in increasing order from the upstream end (pool 1 - just downstream of the confluence with Bitch Creek at RM 16.1) to the downstream end (pool 27 - just upstream of the confluence with Canyon Creek at RM 5.0). An additional section just downstream of pool 1 that contains two long cobble bars was also modeled (labeled as cobble bars).

The hydraulic model was divided into two reaches: Bitch Creek to Spring Hollow (Pools 1-9) and Spring Hollow to Canyon Creek (Pools 10-27). Cross-section locations are identified by river miles from the Teton Dam site. Each cross section can also be identified by the pool it was surveyed in, followed by the sequential cross-section number within the pool (increasing in the downstream direction). For example, in pool 1, five cross sections were surveyed. The upstream-most cross section would be 1-1 (RM 16.11), the next downstream cross section would be 1-2 (RM 16.09), and so forth. The riffles and rapids that presently form the 27 pools in this reach include drops in water surface of 2 to16 feet (refer to tables 3 and 4).

The landslide debris fans that form the riffles and rapids act as the hydraulic control for each pool. Therefore, every pool water surface elevation is a function of the water surface elevation at the top of the corresponding rapid. The water depth at these hydraulic control sections is at the minimum specific energy (critical depth) and can be computed directly because it is only a function of the channel geometry and discharge (not channel roughness). This means that the hydraulics in each pool are independent of one another.

The drop in water surface elevation through the chutes, riffles, and rapids was measured during the surveys. The wetted width of these sections were measured in the field or estimated from the aerial photographs. However, the details of the channel-bottom topography through the high-velocity chutes, riffles, and rapids are not well known because of the inability to survey these sections. Therefore, the model's hydraulic predictions through these short, high-velocity reaches may not be very accurate and are not reported in this study.

To model the hydraulics through each rapid, two cross sections were developed, one at the top of the rapid (upstream end) representing the hydraulic control, and the other at the bottom of the rapid (downstream end) representing the start of the next pool downstream (figure 5). The importance of the cross section at the bottom of the rapid is to define the water surface slope through the rapid. The water surface elevation at the bottom-of-rapid cross section is entirely dependent on, and essentially equal to, the water surface elevation of the next cross section

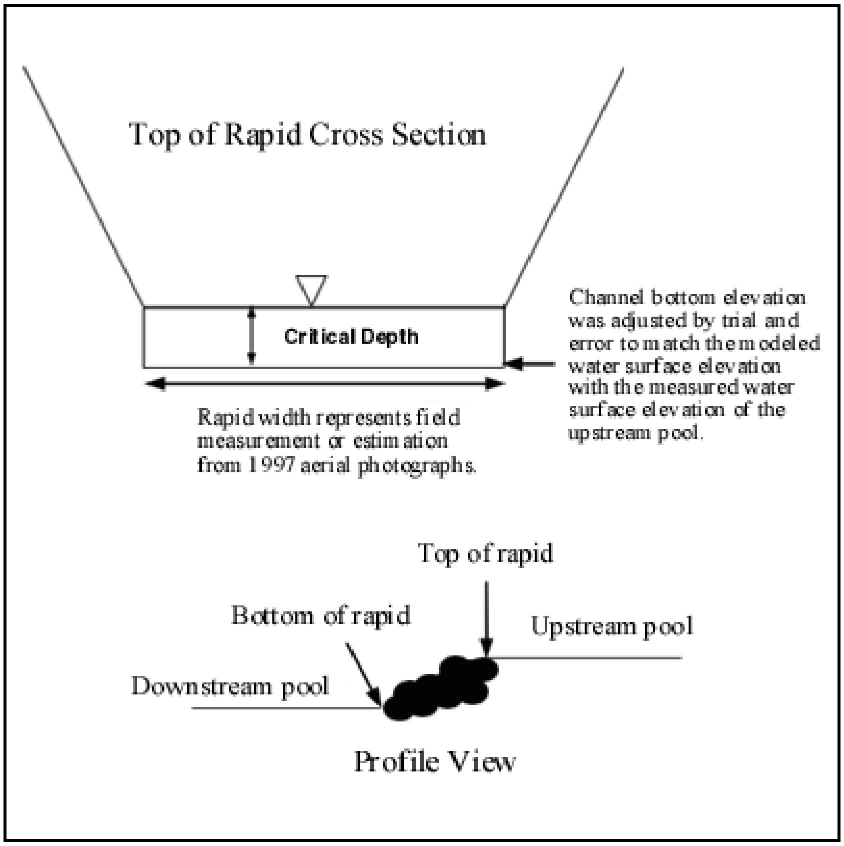

Figure 5.—Illustration of rapid cross section developed for hydraulic model and profile view of rapid section.

downstream (cross sections are relatively close). Also, the water surface elevation at the bottom-of-rapid cross section has no effect on the water surface elevation at the top of the rapid because the top of the rapid is a hydraulic control section. Therefore, the water surface elevation is not sensitive to the exact cross-section shape at the bottom of the rapid.

A simple trapezoidal shape was assumed for the overbanks for the top and bottom rapid cross sections with a rectangular section added to the lower portion to represent the rapid area (figure 5). The cross-section width for the top of each rapid was set equal to the width measured in the field or estimated from 1997 aerial photographs. The depth of the rectangular portion for the top of each rapid was set equal to the computed critical depth for that section (based on width and discharge). The cross-section width for the bottom of each rapid was set to be the average of the width at the top of the rapid and the width of the next measured cross section in the downstream pool. The channel-bottom elevation for the section at the downstream end of the rapid was set equal to the thalweg elevation of the next measured pool cross section.

Additional cross sections were interpolated by the HEC-RAS model to fill in gaps where there were long distances between measured cross sections. A downstream boundary condition (necessary for the subcritical flow regime computations) of critical depth was used at the downstream-most cross section for each model. For the Bitch Creek to Spring Hollow model, rapid 9 was used as the downstream boundary location. For the Spring Hollow to Canyon

Creek model, the last rapid (rapid 27) upstream from Canyon Creek was used (photograph A-21). The travel time for water was also computed, based on velocity and length of each pool. A hydraulic summary of the travel time, mean velocity, and maximum depth for each pool is presented (tables 12 and 13).

To calibrate the model, the channel-bottom elevation for the hydraulic controls (upstream end of each rapid section) was adjusted by trial and error until the modeled water surface elevation in the upstream pool (formed by the rapid) matched the mean water surface elevation measured in the field (at a discharge of 670 cubic feet per second for the Bitch Creek to Spring Hollow model and at 1,400 cubic feet per second for the Spring Hollow to Canyon Creek model).

Once the model is calibrated, the hydraulics for any discharge can be computed through the river reach. To evaluate the hydraulics at a typical summer discharge, the model was also run at a steady flow of 1,000 cubic feet per second (table 12).

Water Surface Profiles.—Several plots were generated from the output data computed by the hydraulic model. Longitudinal water surface profiles are provided that were computed for the flood peaks corresponding to a typical summer discharge of 1,000 cubic feet per second and the 2- and 100-year floods (figures H-1 and H-2) and the median flows for May, June, July, August, and September (figures H-3 and H-4).

Based on the model results, the water surface elevations in the pools raise 2 to 3 feet when flows increase from 1,000 cubic feet per second to the 2-year flood of 3,440 cubic feet per second, and another 2 to 3 feet when flows increase to the 100-year flood of 7,410 cubic feet per second. During the summer months, when flows fluctuate, on average, from 629 to 1,910 cubic feet per second, pool elevations fluctuate less than 1 foot.

Mean Velocity.—Mean velocity versus river mile was plotted for the flood peaks corresponding to a typical summer discharge of 1,000 cubic feet per second and the 2- and 100-year floods (figures H-5 and H-6). The graphs show how the velocities are fairly consistent through the deep pools, but increase rapidly to high levels as the water passes through a rapid or riffle.

The modeled flood peaks result in a range of pool velocities from 1 to 7 feet per second. Although the 100-year flood peak of 7,410 cubic feet per second is more than double the 2-year flood peak of 3,440 cubic feet per second in flow magnitude, only a small increase in velocity of just over 1 foot per second results in most pools. Pool velocities are typically a maximum of 2 feet per second during summer.

Table 12.—Hydraulic summary table for existing conditions from Bitch Creek to Canyon Creek at a discharge of 1,000 ft^3/s

	River mile from Teton Dam site	Number of survey lines used in model	Length of section (ft)	Travel time (hrs)	Mean velocity (ft/s)	Maximum depths (ft)
Felt Dam	19.1		-	-	-	-
Badger Creek	18.5		-	-	-	-
Bitch Creek	17.4		-	-	-	-
Pool 1	16.1087 to 16.0599	5	260	.1	1.5	17
Cobble bars	16.0085 to 15.9195	5	470	.1	1.1	11
Pool 2	15.8365 to 15.5791	7	1,360	.2	1.6	8
Pool 3	15.3916 to 14.9399	10	2,390	.3	2.0	13
Pool 4	14.8452 to 14.0832	15	4,020	1.2	.9	15
Pool 5	13.7408 to 13.2138	14	2,780	1.1	.7	19
Pool 6A	13.1191 to 12.7642	9	1,870	.8	.6	20
Pool 6B	12.6802 to 12.6684	2	60	.1	4.2	4
Pool 7	12.5854 to 12.4525	4	700	.2	1.0	10
Pool 8	12.3613 to 12.2624	2	520	.1	1.6	9
Pool 9	12.2333 to 12.1341	3	520	.1	1.4	10
Spring Hollow	12.1	-	-	-	-	-
Felt Dam	19.1		-	-	-	-
Badger Creek	18.5		-	-	-	-
Bitch Creek	17.4		-	-	-	-
Spring Hollow	12.1		-	-	-	-
Pool 10	12.063 to 11.917	3	769	0.1	1.4	8
Pool 11	11.898 to 11.517	4	2,013	0.5	1.1	10
Pool 12	11.504 to 11.136	7	1,941	0.6	0.9	18
Pool 13	11.117 to 10.909	2	1,100	0.2	1.8	12
Pool 14	10.814 to 10.492	3	1,702	0.5	0.9	16
Pool 15	10.445 to 10.165	3	1,479	0.7	0.6	21
Pool 16	10.032 to 9.903	3	681	0.1	1.7	11
Pool 17	9.884 to 9.734	3	794	0.4	0.6	14
Linderman Dam	9.734		-	-	-	-
Pool 18	9.722 to 9.623	2	524	0.3	0.6	26
Pool 19	9.537 to 9.158	4	2,005	0.7	0.8	11
Pool 20	9.063 to 8.978	1	450	0.1	1.4	10
Pool 21	8.959 to 8.618	4	1,801	0.4	1.2	10
Pool 22	8.552 to 8.414	2	728	0.2	1.1	8
Pool 23	8.395 to 8.112	4	1,498	0.3	1.4	11
Long chute of riffles	7.979 to 7.502		2,097	0.1	3.9	-
Pool 24	7.502 to 6.962	6	2,851	0.4	2.0	8
Pool 25	6.943 to 5.956	9	5,215	1.4	1.0	14
Pool 26	5.918 to 5.471	6	2,359	1.2	0.5	19
Pool 27	5.442 to 5.347	2	504	0.2	0.8	12
Canyon Creek	5.000		-	-	-	-
Canyon Creek to borrow ponds	5.000 to 1.490		19,765	-	-	-
Borrow ponds	1.490 to .4		7,867	-	-	-

Predam (1972) Conditions Hydraulic Model

To create a hydraulic model of predam conditions prior to the 1976 landslides, existing cross-section data were adjusted, based on estimated changes in the channel bottom (detailed in appendix K). The aerial photographs were used to determine which, if any, ripples and rapids existed prior to the 1976 landslides. The channel bottom elevations of pools 1, 2, and 3 did not need to be altered to re-create predam water surface elevations, only the rapids needed to be removed. However, the lower two-thirds of pool 4 needed to be lowered significantly to re-create predam water surface elevations that corresponded to the 1972 contour elevations. In pools 5 to 9, only one cross section at the upstream end of pool 5 had to be lowered, along with the rapids to re-create predam water surface elevations.

It was determined that all the rapids had been either newly created or enlarged from the 1972 conditions (refer to tables 9 and 10). The 1976 landslide debris raised the channel bottom and constricted the channel width in rapid locations. Typical channel widths in 1972 were about 200 feet, but 1976 landslides have often constricted the river to half this width at rapid and riffle locations. Based on aerial photograph analysis and field observations, it was also determined that there were four locations between Bitch Creek and Canyon Creek where the river had not changed since 1972. These locations were upstream of pool 1, near Spring Hollow, the long chute of riffles downstream from pool 23, and the bottom of rapid 27 at the end of the modeled reach. Linderman Dam was the only portion of the river that had a higher water surface elevation in 1972 than the existing water surface elevation. In 1972, Linderman Dam created a 10-foot drop in water surface and formed a 3,600-foot-long pool upstream. Linderman Dam has since been partially removed. The remainder of the dam causes a 2-foot drop in water surface but does not significantly back up water past pool 17.

To calibrate the model of predam conditions, the existing water surface elevation (at 739 cubic feet per second) was compared to the water surface elevation contours of the 1972 topographic maps (developed at 739 cubic feet per second). In locations where the water surface elevations did not match, existing cross sections were altered so that the modeled water surface elevation would match 1972 topographic map water surface elevation contours (figures H-11 and H-12). Alterations consisted of adjusting channel bottom elevations and top widths to represent estimated predam conditions prior to the constrictions caused by the 1976 landslides. Notice that the modeled predam water surface still has a riffle and pool-type profile.

At the upstream end of the reach, a rapid just upstream of rapid 1 formed a pool behind it in 1972 and is now inundated. If rapid 1 is removed to re-create predam conditions, the 1972 rapid still results in a pool water surface, similar in elevation to what rapid 1 creates today.

With the exception of Linderman Dam, from pools 10 to 24, only the channel-bottom elevations of the rapid cross sections were lowered to create a water surface profile that matched the 1972 profile at the top or middle of the pool. The cross section representing Linderman Dam was raised to recreate the 1972 water surface when the dam was in operation. In pools 25 to 27, pool and rapid cross sections were widened (where constrictions did not exist in 1972) to have an average channel top width of 200 feet and lowered to match the 1972 water surface profile. The plots in appendix E show the changes made to the existing cross sections in pools 25 to 27 to create the 1972 channel bottom. Changes made at rapid cross sections are not shown because of the simple trapezoidal shape.

Comparison Between Existing (1997-98) and Predam (1972) Conditions

To evaluate the changes in modeled water surface and thalweg profiles from predam (1972) to existing (1997-98) conditions, plots were developed based on a typical summer discharge of 1,000 cubic feet per second (figures 6 and 7). The red lines show where the existing channel bottom is higher today than it was in 1972. In pool 4 (RM 14.1 to 14.8) and pools 25-27 (RM 5.3 to 6.9), the water surface and channel thalweg have significantly increased due to landslides in 1976. In addition, several of the rapids are higher in elevation today, causing longer pools to form upstream than the short pool and riffle sequence common in 1972. The 1972 water surface is lower than existing conditions in all reaches of the river except for upstream of Linderman Dam (pools 16 and 17 – RM 9.7 to 10.0).

The mean velocity versus river mile was plotted for the 1997 and 1972 conditions at 1,000 cubic feet per second (figures 8 and 9). In pools 1, 8, and 9 (RM 16.1, and RM 12.1 to 12.4, respectively), the predam velocities are identical to existing conditions, indicating that these pools existing to near the same depths at which they exist today. In pools 2-7 (RM 12.5 to 15.8), the predam velocities were higher than existing conditions. The velocity profiles indicate several riffles served as hydraulic controls in these pools in 1972, in different locations than some of the 1976 landslides. These riffles are now inundated, due to the raised water surface elevation of the pools as a result of the 1976 landslides. The predam velocities are slightly higher in pools 10 to 13 (RM 12.1-10.9) and pools 18 to 22 (RM 9.7-8.4), and slightly lower in pools 14 to 16 (RM 10.8-9.9), where Linderman Dam was backing up water in 1972. Downstream from pool 22 (RM 8.5-5.3), velocities in the predam model are up to 6 feet per second higher than under existing conditions. This is because the rapids forming these pools were not present in 1972.

Teton River From Canyon Creek to Borrow Ponds (Representative Section at RM 4)

A hydraulic model was created for a short reach of river downstream from Canyon Creek at RM 4. Although only 800 feet long, this reach of river is representative of the shallow pool-riffle sequence present in the reach of river from Canyon Creek downstream to the borrow ponds. This reach of river channel was relatively unaffected by landslide debris. The majority of debris fell onto terraces on either side of the river channel and finer sediment most likely entered the river channel and was immediately transported downstream. No large rapids were formed in this reach from 1976 landslides.

Two cross sections were surveyed upstream and downstream from a short riffle at RM 4 (appendix F). In addition to channel bottom topography, the right overbank was surveyed. The right overbank consists of wide terraces that were modeled to determine what high flows would overtop the terraces. A Manning's roughness coefficient of 0.035 was used. The assumptions of normal depth, subcritical flow, and a channel slope of 0.002 were used for the downstream boundary condition.

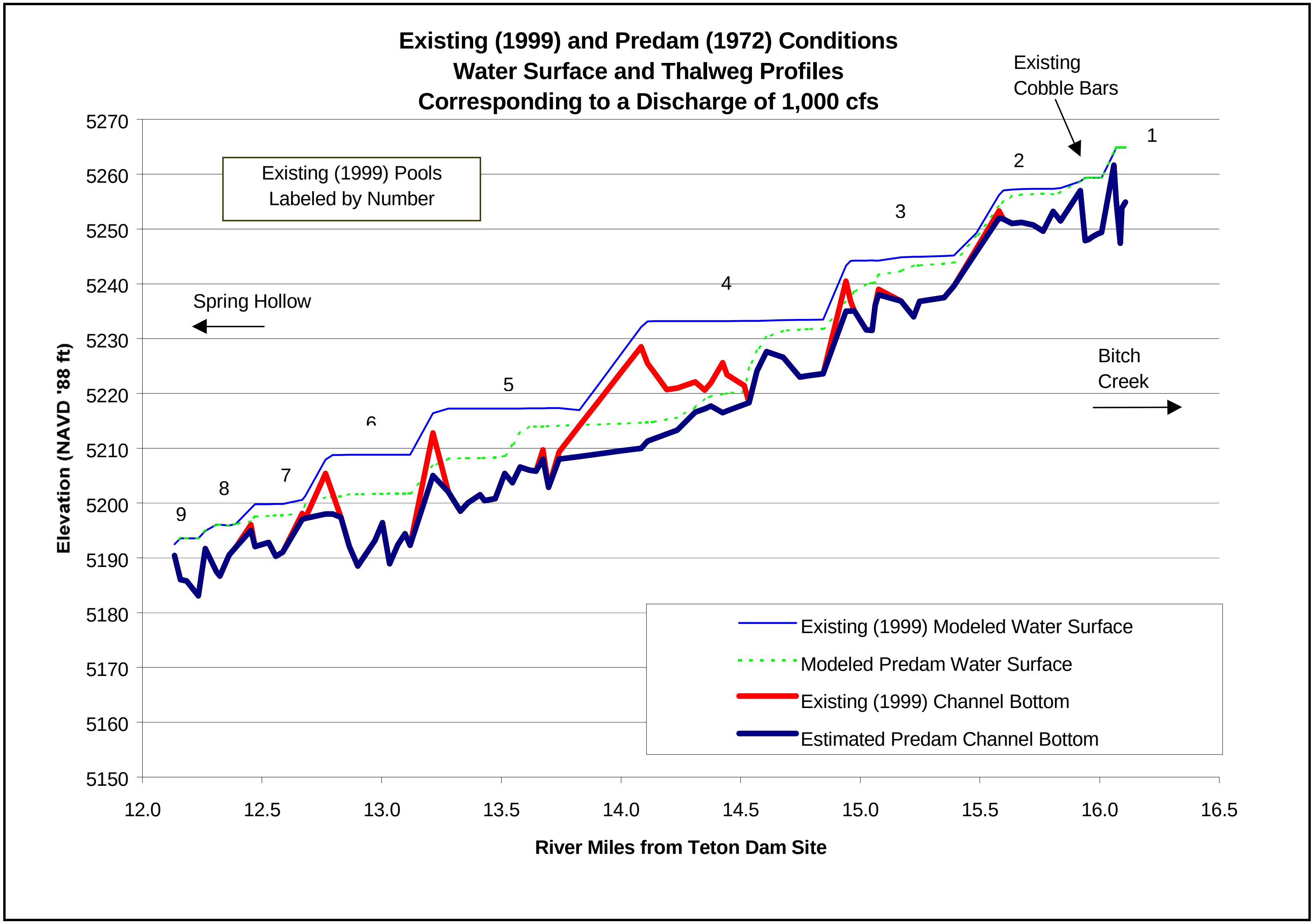

Figure 6.—Comparison of existing (1999) and predam (1972) water surface and thalweg profiles (RM 12.1 to 16.1).

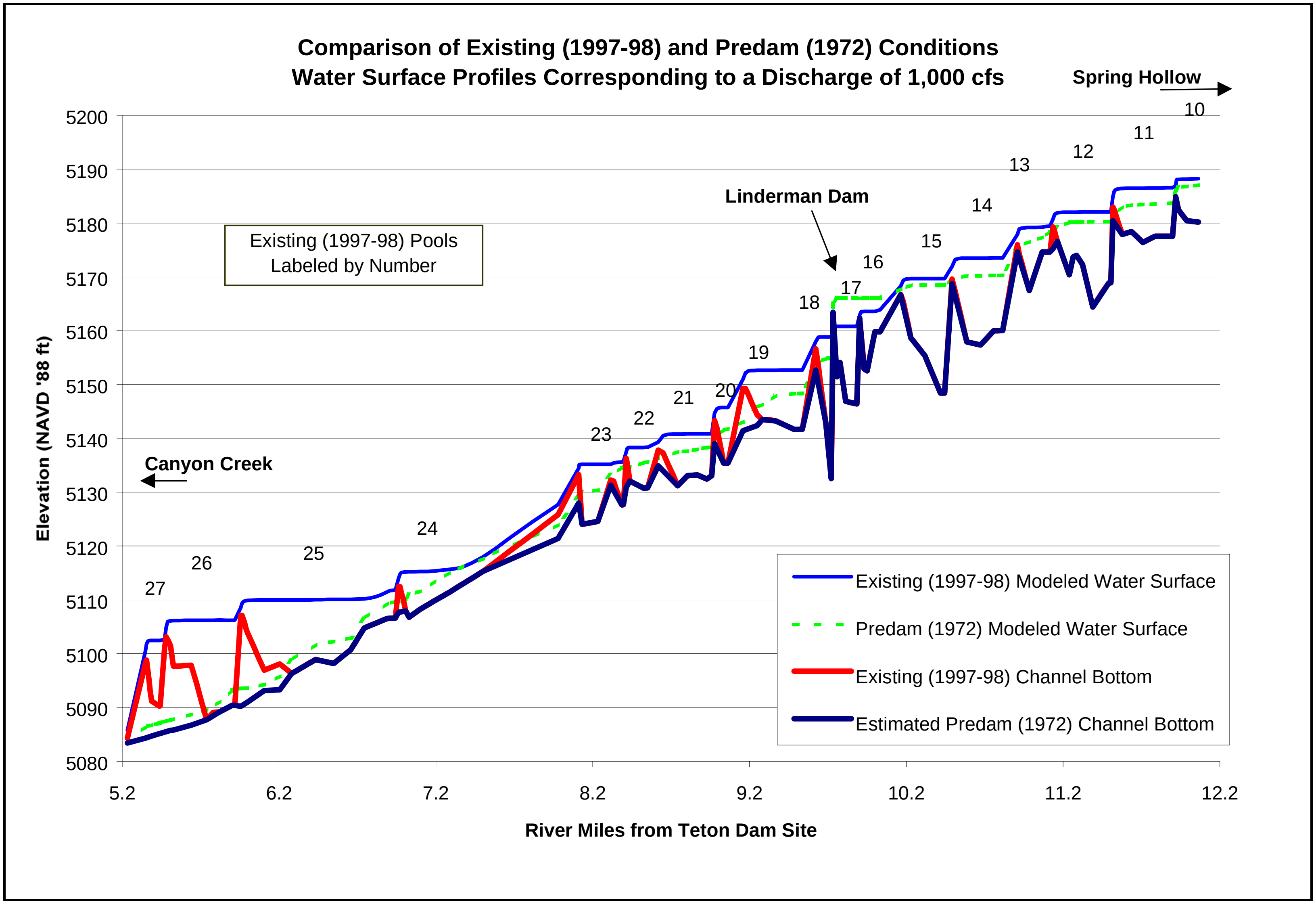

Figure 7.—Comparison of existing (1997-98) and predam (1972) water surface and thalweg profiles (RM 5 to 12.1).

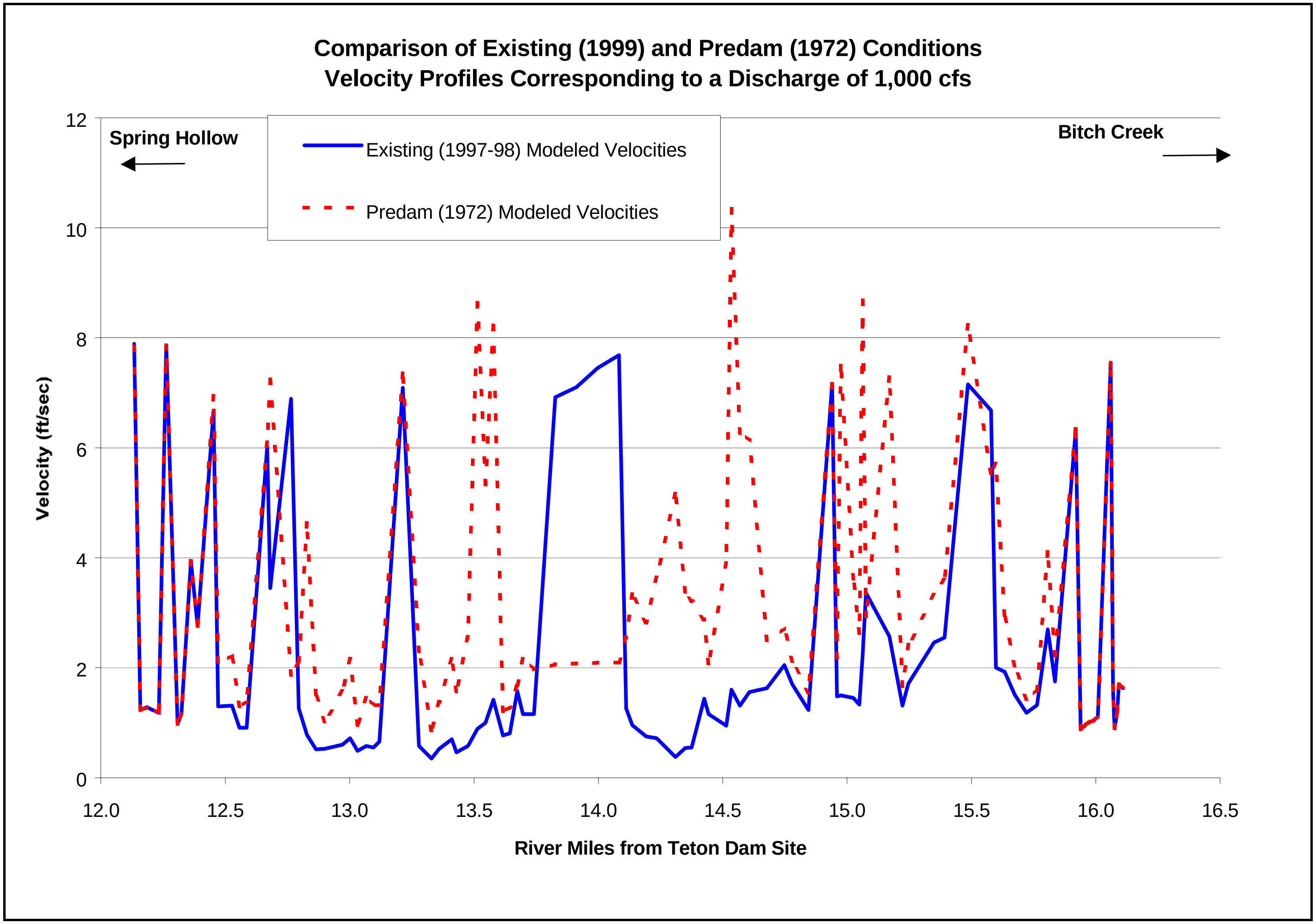

Figure 8.—Comparison of existing (1999) and predam (1972) velocity profiles (RM 12.1 to 16.1).

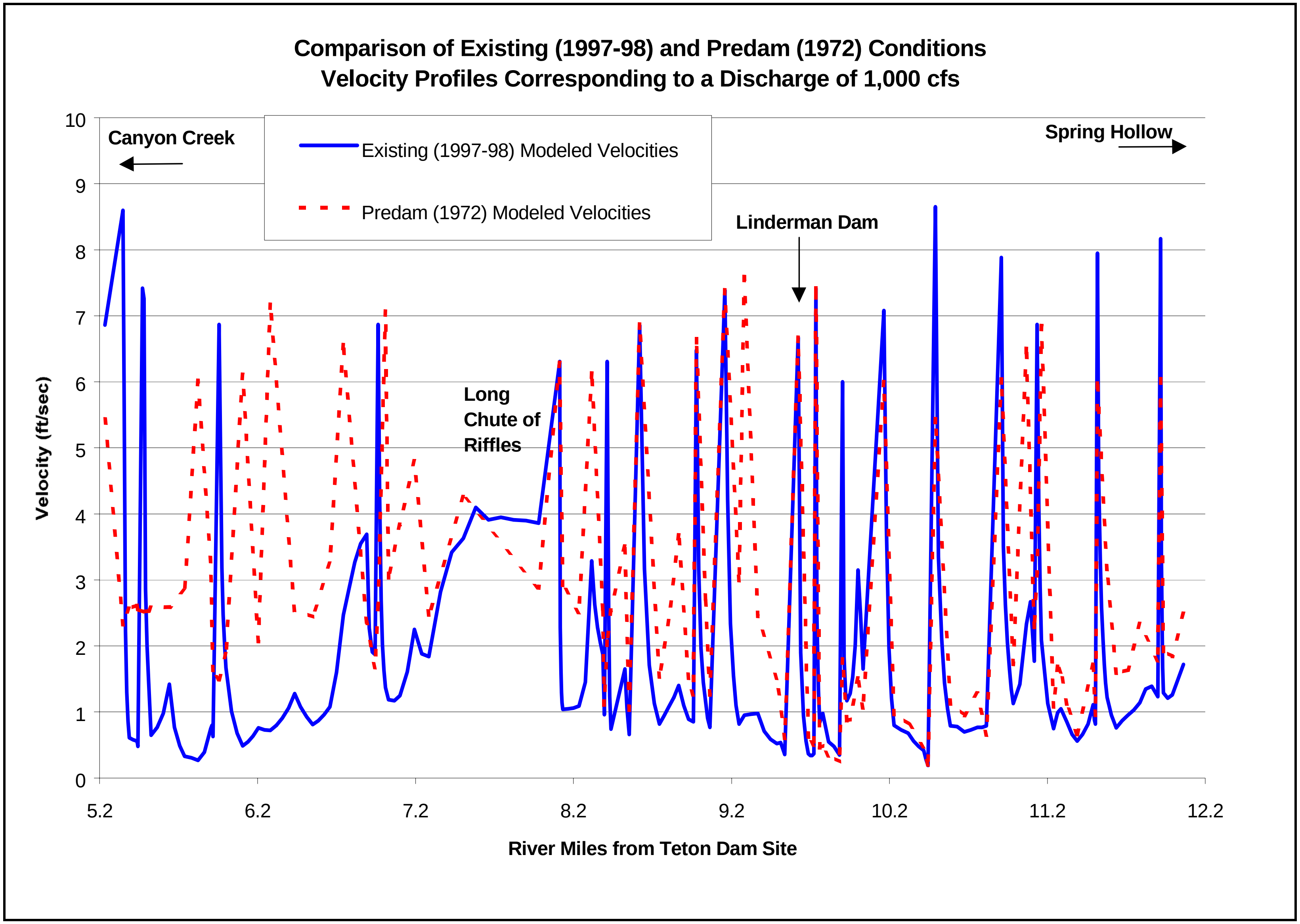

Figure 9.—Comparison of existing (1997-98) and predam (1972) velocity profiles (RM 5 to 12.1).

A summary of the hydraulic model results is presented in table 13. All of the sections have a similar top width (around 100 feet), but the riffle has significantly less flow area and higher velocities than the sections just upstream and downstream. The water surface profiles for the flood peaks versus river mile corresponding to the 2 and 100-year floods were plotted (figure H-7). All of the modeled flood peaks were also plotted at the upstream cross section (RM 4.086) to illustrate the typical scale of the right bank terrace (figure H-8). Model results show it would take a discharge greater than the 100-year flood peak to significantly inundate the high flood terrace on the right canyon wall.

Table 13.—Hydraulic properties of the Teton River at RM 4 at a discharge of 1,000 ft^3/s

River mile from Teton Dam site	Mean velocity (ft/s)	Maximum depth (ft)	Flow area (ft^2)	Top width (ft)
4.086	2.0	8	503	108
4.057	1.9	8	534	97
4.038	5.5	2	183	109
4.001	6.5	2	156	106
3.968	2.9	5	351	118
3.938	3.5	4	283	110

The computed velocities were plotted versus river mile corresponding to the flood peaks for the 2- and 100-year floods and a typical summer discharge of 1,000 cubic feet per second (figure H-9). Velocities in this reach of river range anywhere from 1 to 10 feet per second. The velocities in this reach increase much more rapidly with increases in discharge than the velocities in the deep pools in the Spring Hollow to Canyon Creek reach.

Borrow Ponds to Just Upstream From Teton Dam Site (RM 1.5 to 0.3)

The model of the borrow ponds consists of two large ponds connected by a narrow reach of river. This model was based on 27 cross sections measured in 1997 (appendix G). The narrow channel that runs parallel to the downstream borrow pond next to the Teton Dam site was not included in the model upstream from the point where the flow from the borrow ponds enters this channel (cross sections DC1 and DC2); however, the downstream-most cross section (DC3) was included (appendix G). A Manning's roughness coefficient of 0.035 was used. The borrow pond water surface elevation of 5045.8 feet (from the 1997 survey data) was used to satisfy the downstream boundary condition required for subcritical flow computations.

A summary of the hydraulic properties for the borrow ponds, including maximum depth, flow area, top width, and mean velocity, is presented for a typical summer discharge of 1,000 cubic feet per second (table 14). The total volume in the borrow ponds is approximately 1,000 acre-feet. Top widths range from 260 to 760 feet in the ponds. The channel connecting the ponds is approximately 100 to 150 feet wide. The water surface and channel bottom profile were plotted at a typical summer discharge of 1,000 cubic feet per second (figure H-10).

Table 14.—Hydraulic properties of the borrow ponds for a discharge of 1,000 ft^3/s

River mile from Teton Dam site	Mean velocity (ft/s)		Maximum depth (ft)	Flow area (ft^2)	Top width (ft)
1.490	0.5	Upstream end of borrow ponds	13	2,035	295
1.453	0.3		17	3,746	369
1.406	0.5		11	2,232	361
1.310	0.5		10	1,873	303
1.264	0.4		16	2,793	261
1.146	0.2		18	4,665	337
1.129	0.1		27	10,071	490
1.071	0.1		28	11,799	586
0.972	0.1		29	10,169	462
0.934	0.1		31	10,287	475
0.881	0.1		34	16,385	663
0.827	0.1		35	15,908	759
0.795	0.1	End of upstream borrow pond	36	11,124	396
0.774	3.6	Constriction	4	281	109
0.746	2.3	Constriction	8	436	96
0.727	0.5	Constriction	22	1,974	166
0.702	0.1	Start of downstream borrow pond	36	8,508	336
0.650	0.1		41	10,859	367
0.601	0.1		43	11,710	381
0.547	0.1		41	10,041	370
0.495	0.1		39	9,976	379
0.454	0.2		17	4,297	372
0.434	0.5		10	1,982	331
0.394	0.2		21	4,456	283
0.376	0.2	End of downstream borrow pond	22	4,775	333
0.348	0.6	Entrance to diversion channel	20	1,745	171
0.320	0.6	Diversion channel	12	1,698	219

Travel Time of Water

Once the hydraulic model was complete, the velocities computed at each of the cross sections were used to compute the travel time of water for predam and existing conditions (table 15).

Table 15.—Estimated travel times of water for existing and predam conditions at 1,000 ft^3/s

River mile from Teton Dam site	Teton River reach	Travel times of water at 1,000 ft^3/s (hrs)	
		Existing (1997-99) conditions	Predam conditions (prior to borrow ponds)
16.1 to 12.1	Bitch Creek to Spring Hollow	4.8	2.6
12.1 to 9.7	Spring Hollow to Linderman Dam	3.5	3.2
9.7 to 7.5	Linderman Dam to pool 24	2.6	1.5
7.5 to 5.0	Pool 24 to Canyon Creek	3.3	1.1
5.0 to 1.5	Canyon Creek to borrow ponds	1.6	1.4
1.5 to dam site	Borrow ponds to Teton Dam site	13.2	0.6
	CUMULATIVE:	29.0 hours	10.5 hours

The travel time from one cross section to the next was computed by dividing half the distance between the cross sections by the upstream cross-section velocity, dividing the other half of the distance by the downstream cross-section velocity, and then adding the two travel times together. For the predam conditions through the borrow ponds, it was assumed the borrow ponds had not yet been constructed, and an average velocity of 3.7 feet per second from the reach at RM 4.0 was used from Canyon Creek all the way to the dam site. The estimated travel times through Teton River at 1,000 cubic feet per second from Bitch Creek to the dam site were plotted (figure 10).

Travel time through the rapids is very fast, as expected, and travel time through the pools depends on both the length and depth of the pool. The deeper or longer the pool, the greater the travel time. The travel time through the Bitch Creek to Canyon Creek reach has increased the most between pool 24 and the confluence with Canyon Creek, where deep pools exist that did not exist prior to the 1976 landslides. The borrow ponds have increased the travel time through the last 1.5 miles upstream from the dam site by a maximum of 12.6 hours. However, the actual increase may have been less. This is because the hydraulic model did not include the river channel that can bypass flow around the downstream borrow pond. Further, because the model is one-dimensional, any potential eddy or density currents in the borrow ponds were ignored. Eddy or density currents in the borrow ponds would decrease the effective flow area through the ponds and increase flow velocity, which, in turn, would decrease travel time.

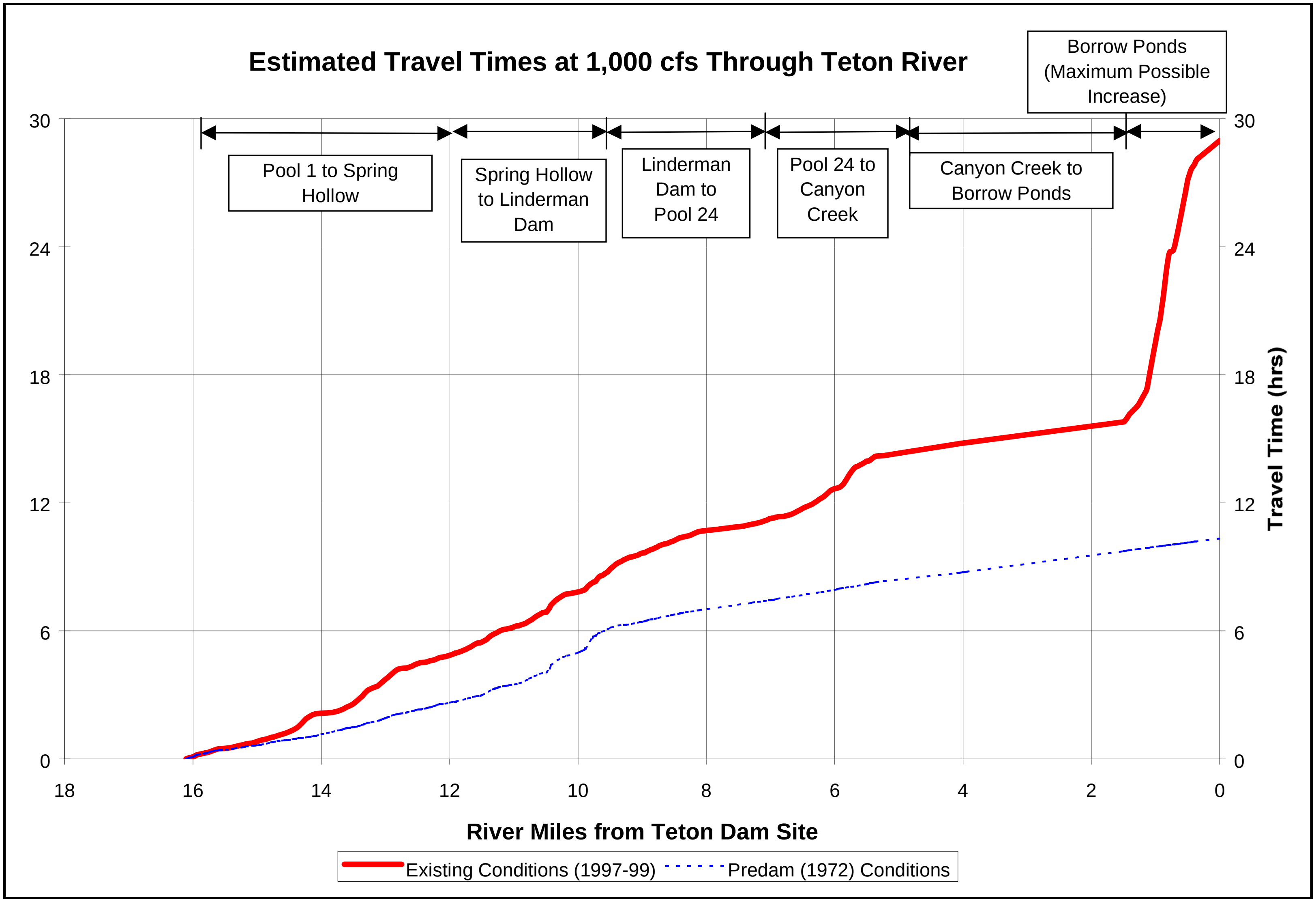

Figure 10.—Estimated water travel times corresponding to a typical summer discharge of 1,000 ft³/s for existing (1997-99) and predam (1972) conditions in the former Teton Reservoir area.

Water Temperature

Increased temperature is postulated to result from the increased travel time, and shallow, lower velocity, larger surface area pools resulting from the many small landslides induced by inundation and dam failure that are partially blocking flow. Temperature data collection and analysis to determine likely increase in summer temperatures due to increased travel times in pools was performed during the summer of 1998 (Bowser, 1999) (figure 11). The construction and subsequent failure of Teton Dam has likely increased summer river water temperatures by 1 to 2 degrees F. Temperatures have increased because flows today move slower through the river pools enlarged by 1976 landslides and through the borrow ponds excavated for the construction of Teton Dam. The loss of riparian trees, especially in the reach downstream of Canyon Creek, also would have contributed to increased river temperatures. Suitable temperatures probably still exist in the deeper portions of the borrow ponds and river pools upstream of Canyon Creek. Most of the temperature gain occurs along the reach of river between pool 24 (7 ½ miles upstream of Teton Dam) downstream to the confluence with Canyon Creek, and in the borrow ponds.

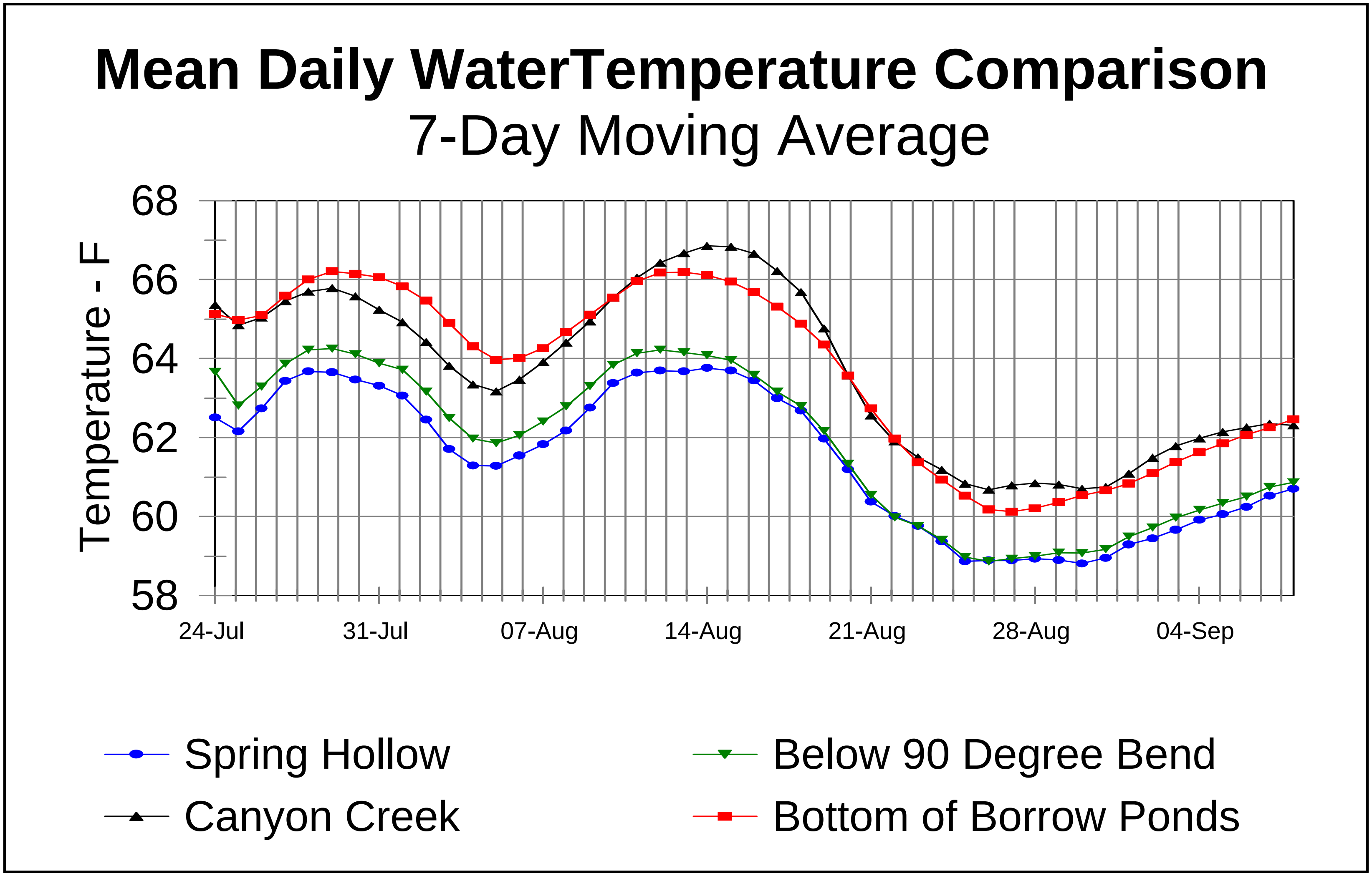

Figure 11.—Comparison of mean daily water temperatures collected in the Teton River (July 24, 1998, to September 9, 1998) at the locations of Spring Hollow, Canyon Creek, just downstream from a large bend in pool 24, and at the downstream end of the borrow ponds (Bowser, 1999).

Section 6

Major Findings and Conclusions

The Teton River canyon was affected by landslides that were caused by the inundation of Teton Reservoir and the subsequent failure of Teton Dam in 1976. Prominent landslide scars and debris fans are now common features along the Teton River canyon for nearly 17 river miles upstream from the Teton Dam site. The upstream extent of the canyon affected by the landslides is approximately 1 mile downstream from the confluence with Bitch Creek. The most significant impacts on the Teton River channel occurred in an 11-mile reach stretching from the upstream end (just downstream from Bitch Creek) downstream to the confluence with Canyon Creek.

Landslide Activity and Material

Landslide activity has been an ongoing natural geomorphic process in the Teton River canyon ever since the placement of the Huckleberry Ridge tuff and uplift of the Rexburg Bench. Landslide activity in the reservoir area started with the filling of the reservoir (Reclamation, 1976). The June 5, 1976, dam failure activated more than 200 landslides along the reservoir rim, due to the filling and the rapid drawdown of the reservoir. Approximately 1,460 acres of canyon slopes were submerged by the reservoir, and 34 percent (500 acres) failed. Approximately 3.6 million cubic feet of material moved downslope to the canyon floor, with some reaching and blocking the river. While a large amount of landslide material reached the valley floor, much of the debris remained on the lower portion of the slopes. Most of the landslides were shallow surface slumps, earth flows, debris flows, and rockfall. The thickness of the landslide debris ranged from less than 5 feet to about 25 feet.

Particle size evaluation of landslide material was completed during the 1998 field investigations along the Teton River, but should be considered preliminarily due to the small data sample. The size of the landslide material on the valley floor and lower portion of the slopes ranges from silt to boulders greater than 10 feet across. Most of the material in the landslides consists of rock fragments from 3 inches to 3 feet in diameter. This is consistent with particle size data estimated for the material on the predam reservoir slopes.

Landslides in the Teton River Canyon are an integral part of the canyon evolution. The construction and failure of the Teton Dam have rapidly accelerated those processes in the portion of the river canyon below the high elevation of the former reservoir. The 1976 landslides also significantly reduced the volume of source material available (below the former reservoir level) for future landslides. Therefore, the probability and quantity of future landslides (initiated below the elevation inundated by the former reservoir) have been significantly reduced over the next several centuries to thousands of years.

The 1976 landslides removed material from the lower canyon slopes which could tend to make the upper canyon slopes less stable. However, there is no evidence (through September 1999) that large landslides have occurred in the upper canyon slopes in the last two decades since the failure of Teton Dam. Although the upper canyon slopes have been relatively stable during the last two decades, the probability of future localized landslides on the upper canyon slopes (initiated at elevations above the former reservoir level) may have increased because of material removed from the lower canyon slopes.

Rapids and Pool Formation

Within the study reach from Bitch Creek to Teton Dam, the Teton River canyon is narrowest at the upstream end and tends to become progressively wider in the downstream direction. As the canyon widens out, terraces along both banks of the river widen out also. Upstream from the confluence with Canyon Creek, the Teton River canyon was narrow enough that the 1976 landslide debris fans typically reached the river channel. These debris fans formed new rapids in some locations and enlarged pre-existing riffles in other locations. The pre-existing riffles were formed by landslides that occurred centuries ago through natural geologic processes. Resulting from the failure of Teton Dam in 1976, 27 rapids or riffles and pools have persisted in the reach upstream from Canyon Creek (17 rapids and 1 riffle between Canyon Creek (RM 5) and Spring Hollow (RM 12.1) and 7 rapids and 2 rapid and riffle combinations upstream from Spring Hollow). Landslides also deposited debris in river-channel pools upstream from some of these rapids. Downstream from Canyon Creek, the Teton River canyon was wide enough that the landslide debris was deposited on the surface of the adjacent river terraces and typically did not reach the river channel. Therefore, the river channel was not significantly constricted by landslides downstream from Canyon Creek, and the hydraulics are relatively the same as in predam conditions.

Landslides have been naturally creating rapids and pools in the narrowest reaches of the Teton River canyon for thousands of years. For example, a debris flow that occurred during the last decade enlarged a major rapid and pool in the narrow reach between Badger Creek and Bitch Creek. This reach of the river is upstream from the area inundated by Teton Reservoir. Fluvial processes have also been at work for thousands of years. All the major rapids formed by prehistoric landslides have been reduced to small rapids and riffles through a gradual reworking of the river channel over a long period of time.

In 1972, two rapids and several small riffles existed between the confluence with Bitch Creek and Spring Hollow. There were no major rapids present along the Teton River between the Teton Dam site and Spring Hollow (based on inspection of aerial photographs). However, 13 riffles and deep pools existed in the 4-mile reach downstream from Spring Hollow (RM 8.0 to RM 12.0). It is estimated that water depths in these pools ranged from 5 to 20 feet. The landslides that occurred in 1976 enlarged many of the existing riffles into rapids and, subsequently, increased pool water surface elevations by 2 to 5 feet (an increase much less than the pool depths). These deep pools measured in 1997 downstream from Spring Hollow must have been present in 1972 because they could not have been created since 1976.

When landslides naturally occurred in the wider reaches of the Teton River canyon (prior to Teton Dam), the river channel was able to move laterally around the debris fan or incise through the area of finest material, and, consequently, deep pools were not able to persist. In contrast, when landslides naturally occurred in the narrow reaches of the canyon, the river channel was completely blocked, the riverflows were forced to spill over the coarse debris, and persistent, deep pools were formed upstream.

The 1976 landslides had the greatest impact on the Teton River channel in the 2-mile reach upstream from Canyon Creek, between RM 5.3 and RM 7.4. In this reach, there is no evidence of deep pools having been present in 1972. However, there are four new major rapids and pools (24, 25, 26, and 27) in this reach today, with pool depths ranging from 8 to 19 feet. The four landslide rapids in this reach have a total drop of over 28 feet over a distance of 2.1 miles. When looking at the impact of these rapids and pools, they must be viewed in sequence. For example, the downstream-most rapid (informally known as Parkinson’s Rapid) has the largest single drop in the river (16 feet), with the exception of rapid 4. The relatively short pool that was formed behind this rapid inundates much of the next rapid upstream (informally known as Little Parkinson's Rapid). If the downstream- most rapid were removed, the next rapid upstream would have an even larger drop than the drop through the existing Parkinson's Rapid.

No large landslides occurred in the half-mile reach downstream from RM 8.0, and the river channel was left relatively unaffected by the initial filling of the reservoir and subsequent failure of Teton Dam. The reason that no large landslides occurred in this reach is likely due to the general northeast-southwest orientation of the canyon in this location. Most of the river canyon is generally oriented in an east-west direction so that the south side of the canyon (left side looking downstream) is more shaded, retains more moisture, and develops thicker soil and forest growth than the north (right) side. The north side of the canyon gets more sun and has less moisture; thus, the canyon-wall surface is typically composed of exposed bedrock. Subsequently, nearly all of the large landslides in 1976 occurred on the south side of the canyon. In the half-mile reach downstream from RM 8.0, both sides of the canyon have significant sun exposure, and there was relatively little soil development and forest growth on either side of the canyon. Consequently, the landslides that did occur in this reach were shallow, and the river channel and hydraulics were left relatively unaffected.

Linderman Dam

Linderman Dam, at the confluence with Milk Creek (RM 9.7), was partially removed prior to the construction of Teton Dam and Reservoir. The dam still has a horizontal concrete beam that extends across a portion of the river at about the level of the water surface (photograph A-32). At low flow, the water surface is below the bottom edge of the concrete beam, while the beam is at least partially inundated at higher flows. Even though the beam may cover a portion of the water surface at higher flows, the water velocities under the beam are still high, which could create a dangerous undercurrent for boaters. There are also four vertical pipes, evenly spaced across most of the dam's crest, that protrude a few feet out of the water. Although the hydraulic drop across Linderman Dam is now only about 2 feet (compared to a 10-foot drop in 1972), the deteriorating condition of the dam (some eroded concrete and exposed metal pipes), the concrete beam that extends across a portion of the river, and the four vertical pipes protruding from the dam's crest pose a safety hazard to boaters and anglers.

Travel Time of Water

The travel time of water flowing through the Teton River canyon from the confluence with Bitch Creek to the confluence with Canyon Creek has increased as a result of the landslide debris fans forming rapids and long, slow-velocity pools in the river channel. At a typical July flow of 1,000 cubic feet per second, the travel time of water has increased from predam conditions by about 6 hours (from 8 to 14 hours). Part of this increase is due to the formation of pool 4, which has a much higher water surface and deeper depths than in 1972. The other part of this increase is mainly due to the four new large rapids between RM 5.3 and RM 7.4. Travel time of water has not changed in the reach between Canyon Creek and the borrow ponds (RM 1.5 to 5.0).

Water travel times may have significantly increased through the two large borrow ponds near the dam (RM 0.4 to 1.5), but the magnitude is not precisely known. The two borrow ponds combined are just over 1 mile in length, contain a total water volume of 1.6 million cubic yards (1,000 acre-feet), and potentially increase water travel times by up to 12.5 hours. However, flow patterns through the borrow ponds are complex, due to the presence of a side channel which can bypass flow around the lower borrow pond and the potential for horizontal eddy currents, density currents, and vertical recirculating zones within each borrow pond. The slow moving, or nearly stagnant, water near the borrow pond surface would undoubtably be warm during the summer months, but the warm surface water may not necessarily mix with the inflowing river water (which may form a density current) and may not result in a substantial increase in water travel time.

Water Temperature

The construction and subsequent failure of Teton Dam has likely increased summer river water temperatures by 1 to 2 degrees F. Temperatures have increased because flows today move slower through the river pools enlarged by 1976 landslides and through the borrow ponds excavated for the construction of Teton Dam. The loss of riparian trees, especially in the reach downstream of Canyon Creek, also would have contributed to increased river temperatures. Suitable temperatures probably still exist in the deeper portions of the borrow ponds and river pools upstream of Canyon Creek. Most of the temperature gain occurs along the reach of river between pool 24 (7 ½ miles upstream of Teton Dam) downstream to the confluence with Canyon Creek, and in the borrow ponds.

In areas where the water temperature may have increased, it seems likely that fish requiring cooler water temperatures could move to deeper depths in pools as needed during the warmer period of the diurnal cycle. This would suggest that the "lifestyle" of native fish may be affected by forcing them to alter their movement patterns to satisfy any need for cooler water temperatures during mid- to late-afternoon. If however, the water temperature increase has occurred at a threshold boundary for fish, the one to two degree increase, along with other water quality and/or biological stressors, may actually be affecting fish mortality, forcing them to seek other habitat.

River Bed Material

An increase in water travel time tends to also increase the sediment trap efficiency of pools. This means that finer-grained sediment particles (less than 2 millimeters; i.e., sand, silt, and clay) may settle out along the pool bottom and become part of the bed material. The change in bed-material particle size, caused by the 1976 landslides, cannot be precisely determined because there is no predam data available. However, bed-material observations and samples collected in the pools upstream from Canyon Creek can be compared with the general characteristics of the channel upstream from pool 1 and downstream from Canyon Creek, which is a gravel-bed river. The bed-material data collected is dependent on discharge, particularly recent flood events, because most of the sediment is moved during high flows. Data collected prior to a flood, or at a low discharge, may give results different from data collected after a flood.

Upstream of the former reservoir inundation area, the river channel is extremely steep and narrow. The sediment transport capacity in this reach is presumably high as a result of the river gradient, narrow widths, and high velocities. Between Bitch Creek and pool 1 (the first pool backed up by a landslide-formed rapid), the river has shallow, uniform depths and the channel bed primarily consists of 3-inch cobbles to 6-foot-diameter boulders. Pool 1 is relatively short, approximately 260 feet in length which results in a short water retention time (on the order of a few minutes). The retention times increase in the downstream direction from pool 1 to pool 3 on the order of minutes. Pool 1 with its short retention time does not trap the majority of fine sediments (clay, silt, and sand) transported by the river system. However, pool 1 would likely act as a trap for gravel and cobbles. Maximum channel depths measured at each cross section in this pool range between 10 and 18 feet. The fact that pool 1 still has significant depths after 23 years since the dam failure and the fact that the majority of the riverbed sediment observed upstream of pool 1 is boulders suggest that the gravel and cobble load of the Teton River is small.

In pools 1-3, the majority of the pools are shallow in depth and the retention times in these pools are short. The only exception is a few areas in pool 3 where depths are greater, but because the channel width also is narrow (half of the typical river channel width), the velocities are high and the retention times are short. Pool 4, approximately 4,020 feet in length, is the longest of the nine pools in the Bitch Creek to Spring Hollow reach and has the longest retention time of over an hour. The majority of the pool has a sand-covered channel bottom. Rippled sand is evident in the downstream half of the pool which indicates small velocities. The majority of sediment downstream of pool 4 to Spring Hollow appears to be silt and clay overlaying the predam riverbed or landslide debris.

On the basis of sediments observed along the channel bed, measured pool depths and channel widths, and computed water velocities and travel times, pools 1-3 appear to be near the maximum storage capacity for sand, while pool 4 is in the process of reaching this stage. Pool 4 has been trapping nearly all of the sand supplied from upstream. Eventually, pool 4 will fill in to a maximum storage capacity and sand-sized sediments will be further transported downstream. Pools with long retention times greater than an hour, such as pool 5, will also begin to fill in with fine sediments. This process to fill pool 4 has taken over 20 years, and can be expected to take near this amount to fill pool 5 and, subsequently, to fill pool 6. Eventually, over hundreds of years, the river will try to come to a stable balance where the ability to transport fine sediments equals the upstream sediment supply so that the net loss or gain of sediment storage from year to year is nearly zero.

On August 26, 1997, 30 bed-material samples were collected from 10 pools (pool numbers 10, 12, 14, 18, 19, 21, 23, 24, 25, and 26) between Spring Hollow and Canyon Creek. Of the 10 pools sampled, 8 of the pools (pool numbers 12, 14, 18, 19, 21, 23, 25, and 26) had at least one sample that was dominated by fine-grained sediment particles (less than 2 millimeters). Three of the pools (12, 25, and 26) had at least one sample that was dominated by silt or clay-size particles (less than 0.0625 millimeters). In relation to travel times, pools 25 and 26 have the longest travel times in this river reach, both over one hour. Pool 12 has the next largest travel time, at slightly greater than half an hour.

The sediment particles along the channel bottom of the pools in this reach are definitely finer than the bed material downstream from Canyon Creek. Since deep pools existed in the canyon between RM 8 to RM 12 in 1972, the change in sediment particle size, if any, is impossible to determine. However, four of the largest pools (4, 5, 25, and 26) were formed as a result of landslides in 1976 and occurred in a reach where deep pools were not present in 1972. Therefore, it is likely that the bed material of these pools is much finer today (dominated by sand, silt, and clay) than it was in 1972 (likely dominated by gravel, cobble, and boulder).

Canyon Creek

Canyon Creek is, by far, the largest tributary to the study reach. This creek was severely impacted by landslides caused by the dam failure, but the landslide debris has not been modified to the same extent as landslide debris along the Teton River. Canyon Creek is narrower and has a steeper gradient, on average, than the Teton River, but the drainage basin area and discharges are much less than those on the Teton River. Although landslide debris in Canyon Creek is of similar size to debris in the Teton River, the low flows of Canyon Creek are much less capable of moving material. As a result, landslides and their impact on the river channel have been modified much less than those along the Teton River.

The debris fans and rapids formed by the 1976 landslides will eventually be eroded by river flows, but this process could take centuries. Since 1976, the finer-grained material in the debris fans has been reworked by riverflows, but the coarsest material was left behind and the rapids and pools are still present. The snowmelt runoff of 1997 produced the largest flood peak since 1976 and was approximately equal to the 100-year flood. Even this large magnitude flood was only capable of minor reworking of the debris forming each rapid. Therefore, the existing rapids are most likely too large to be eroded by a single flood, and the river will take centuries of abrasion and weathering to erode the rapids. This, of course, reflects the rates of natural processes which have been occurring for many thousands of years.

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